Association Between Risk Factors for Atherosclerosis and Mechanical Forces in Carotid Artery

Yinong Jiang, MD; Katsuhiko Kohara, MD; Kunio Hiwada, MD

Background and Purpose—Mechanical stresses on the arterial wall participate in the pathogenesis of atherosclerosis as local factors. The relationships between local mechanical forces and risk factors for atherosclerosis were investigated.

Methods—Mechanical forces on the arterial wall were evaluated in the carotid artery in 117 patients with risk factors for atherosclerosis including hypertension, dyslipidemia, diabetes mellitus, and smoking, as well as in 20 age- and sex-matched normal controls. Circumferential wall tension and shear stress were evaluated with Laplace’s law and a poiseuillean parabolic model of velocity distribution. Circumferential wall strain was also evaluated as carotid mechanical force.

Results—Mechanical forces in subjects with risk factors were characterized by low wall shear stress, high circumferential wall tension, and reduced strain. Systolic blood pressure was significantly negatively associated with shear stress and circumferential wall strain. HDL cholesterol showed a significant positive correlation with shear stress and a negative correlation with wall tension. Fasting blood glucose was significantly associated with shear stress, while smoking showed a negative correlation with shear stress and a positive correlation with wall tension. Accumulation of risk factors was associated with further deterioration of mechanical forces. Furthermore, stepwise regression analysis showed that the number of risk factors was significantly associated with mechanical forces independently of carotid intima-media thickness.

Conclusions—These findings suggest that risk factors for atherosclerosis were associated with alteration of mechanical forces. Consequent alteration in mechanical forces could be an underlying local mechanism for the progression of atherosclerosis. (Stroke. 2000;31:2319-2324.)

Key Words: atherosclerosis ■ carotid arteries ■ risk factors ■ stress, mechanical

Mechanical stresses on the arterial wall have been shown to participate in the pathogenesis of atherosclerosis as local factors.1,2 Wall shear stress and stretch are the most important hemodynamic forces involved, in addition to the radial compressive pressure.1–3 In recent studies, an association between mechanical stresses and atherosclerosis in the carotid artery has been reported.4–9 Shear stress has been shown to be negatively related to carotid intima-media thickness (IMT) in healthy individuals4,7 and patients with diabetes mellitus,6 hypertension,8 and left ventricular hypertrophy.9 Carallo et al7 reported that in healthy individuals, circumferential wall tension was positively correlated with carotid IMT. Since atherosclerosis is a complex trait closely associated with multiple risk factors, including hypertension, dyslipidemia, and diabetes mellitus,10–13 mechanical forces could change in response to these risk factors.

Shear stress is a tangential force on the endothelial surface produced by the friction of blood flow. As the stretch stimulus, mechanical strain produced by the stretch apparatus has been used in vitro,14,15 while as the circumferential wall tension, the normal mechanical force due to transmural pressure has been investigated in vivo.7 In vivo, mechanical strain depends on the property of the artery; circumferential wall tension may result in a larger mechanical strain in an elastic vessel than in a more rigid artery. It has also been shown that circumferential deformation and wall tension may act differently.3 Accordingly, the stretch stimulus can be evaluated as 2 factors in vivo: circumferential strain and mechanical wall tension. However, no study has evaluated circumferential strain and wall tension simultaneously as mechanical stress in vivo.

The objective of the present study was to elucidate the relationship between local mechanical forces and risk factors for atherosclerosis. Furthermore, circumferential strain was also evaluated as mechanical stretch in vivo in addition to wall tension.

Subjects and Methods

Study Population

Participants in the study were 117 subjects with at least 1 of the following risk factors for atherosclerosis: hypertension, dyslipidemia, diabetes mellitus, and/or current smoking. Hypertension was...
defined as systolic blood pressure (SBP) $\geq 140$ mm Hg or diastolic blood pressure (DBP) $\geq 90$ mm Hg without medication in the outpatient clinic on at least 2 separate measurements. Diabetes mellitus was defined as fasting blood glucose $\geq 126$ mg/dL (7 mmol/L), 2-hour blood glucose after oral glucose tolerance test $\geq 200$ mg/dL (11.1 mmol/L), or use of medication for diabetes. Dyslipidemia was defined as total cholesterol $\geq 220$ mg/dL (5.69 mmol/L), and/or HDL cholesterol $\leq 35$ mg/dL (0.90 mmol/L), and/or triglyceride $\geq 150$ mg/dL (1.71 mmol/L). All current smokers smoked $\geq 10$ cigarettes per day, while nonsmokers did not smoke cigarettes at all. Subjects were recruited from consecutive patients who underwent evaluation of hypertension or atherosclerosis at Ehime University Hospital from December 1997 to June 1999. All subjects were untreated or had discontinued their therapy at least 1 week before the investigation. Twenty subjects matched for age and sex and free from any risk factors were recruited as normal controls. All procedures were approved by the ethical committee of Ehime University Hospital. Informed consent to the procedures was obtained from each subject.

**Echo-Doppler Examination of Carotid Artery**

Carotid arteries were evaluated with SSD-2000 apparatus (Aloka Co, Ltd) with a 7.5-MHz probe equipped with a Doppler system, as previously described. In brief, with the neck in slight hyperextension, we obtained an optimal visualization of the common carotid arteries (CCAs) after the subjects rested for at least 10 minutes. From multiple approaches, we detected the presence of discrete segments of atherosclerosis (plaque). Plaque was defined as the presence of wall thickening at least 50% greater than the thickness of the surrounding wall. IMT of the far wall was measured in the right CCA 1 cm proximal to the bulb were recorded with simultaneous ECG and phonocardiogram. M-mode images were obtained in real time. IMT of the far wall was measured in the right CCA 1 cm proximal to the bulb were recorded with simultaneous ECG and phonocardiogram. M-mode images were obtained in real time. End-diastolic (IDd) and peak-systolic (IDs) internal diameters were never taken at the level of a discrete plaque.

Wall Shear Stress

On the day of echo-Doppler examination, blood was withdrawn for the determination of blood viscosity. The blood was anticoagulated with heparin (35 IU/mL). The viscosity was measured with a cone/plate viscometer (Biorheolizer TOKIMEC). The viscosity at shear rates of 375/s and 150/s was obtained, and the regression between shear rate and viscosity was determined for each patient. Between a shear rate of 1000/s and 100/s, blood viscosity has been shown to be linearly related to shear rate. In vivo wall shear rates were calculated with the use of a poiseuillian parabolic model of velocity distribution across the arterial lumen based on the assumption of laminar blood flow, according to the following formulas:

\[
\text{Wall Shear Stress} = \frac{4 \times \text{peak-systolic velocity}}{\text{ID}_d}
\]

**TABLE 1. Demographic Characteristics of Participants**

<table>
<thead>
<tr>
<th></th>
<th>Control Subjects</th>
<th>Subjects With Risk Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>n (M/F)</td>
<td>20 (12/8)</td>
<td>117 (77/40)</td>
</tr>
<tr>
<td>Age, y</td>
<td>57±8</td>
<td>60±12</td>
</tr>
<tr>
<td>Body height, cm</td>
<td>158±11</td>
<td>161±10</td>
</tr>
<tr>
<td>Body weight, kg</td>
<td>56±9</td>
<td>64±15*</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>22.1±2.0</td>
<td>24.5±4.0†</td>
</tr>
<tr>
<td>Hypertension, %</td>
<td>0</td>
<td>86 (76)</td>
</tr>
<tr>
<td>Dyslipidemia, %</td>
<td>0</td>
<td>78 (69)</td>
</tr>
<tr>
<td>Diabetes, %</td>
<td>0</td>
<td>33 (29)</td>
</tr>
<tr>
<td>Current smoker, %</td>
<td>0</td>
<td>74 (63)</td>
</tr>
<tr>
<td>SBP, mm Hg</td>
<td>119±12</td>
<td>146±24‡</td>
</tr>
<tr>
<td>DBP, mm Hg</td>
<td>75±8</td>
<td>84±14*</td>
</tr>
<tr>
<td>Total cholesterol, mmol/L</td>
<td>5.07±0.65</td>
<td>5.56±1.03*</td>
</tr>
<tr>
<td>HDL cholesterol, mmol/L</td>
<td>1.63±0.47</td>
<td>1.27±0.44†</td>
</tr>
<tr>
<td>Triglyceride, mmol/L</td>
<td>1.10±0.59</td>
<td>1.64±0.77†</td>
</tr>
<tr>
<td>Fasting glucose, mmol/L</td>
<td>5.17±0.33</td>
<td>6.17±0.88*</td>
</tr>
</tbody>
</table>

Values are mean±SD.

Peak-systolic shear rate $= 4 \times \text{peak-systolic velocity/ID}_d$

Mean shear rate $= 4 \times \text{mean velocity/ID}_d$

The viscosity in situ, at both peak systolic shear rate and mean shear rate, were calculated from the regression line between shear rate and viscosity for each subject. Peak and mean wall shear stress values were obtained by multiplying shear rate and viscosity, with the assumption that blood is a newtonian fluid.

**Circumferential Wall Tension and Strain**

Peak and mean circumferential wall tension values were obtained by Laplace’s law according to the report of Carallo et al:

Peak circumferential wall tension (dyne/cm) = SBP × (IDd/2)

Mean circumferential wall tension (dyne/cm) = (IDd/2)

Arterial strain in the circumferential direction of the carotid artery was obtained as (IDd – IDs)/IDd (%).17

**Reproducibility of Measurements**

Echo-Doppler evaluation and blood viscosity measurement were repeated every week for 4 weeks in 5 subjects. The variation coefficients averaged 2% and 3% for systolic and diastolic internal diameters, 6% for blood viscosity, and 12% and 9% for systolic and mean blood flow velocity. The variation coefficients averaged 8% for both SBP and DBP. The variation coefficients were 6% and 4% for mean shear stress and circumferential wall tension, respectively. There were no differences in these parameters between 1 week and 4 weeks after the cessation of treatment.

**Statistical Analysis**

All values as expressed as mean±SD. Pearson’s correlation coefficient was used to test the association. ANOVA was used to compare the difference among groups. Stepwise regression analysis was used to evaluate the independent parameters for mechanical stresses. P<0.05 was considered statistically significant.

**Results**

Table 1 summarizes the demographic profiles of control subjects and subjects with risk factors. Atherosclerotic and...
hemodynamic characteristics are summarized in Table 2. All parameters of mechanical forces were significantly different between the 2 groups. Mechanical forces in subjects with risk factors were characterized by low wall shear stress, high circumferential wall tension, and reduced strain.

The relationships between mechanical forces and IMT are illustrated in Figure 1. There was a significant negative correlation between shear stress and IMT and a significant positive correlation between wall tension and IMT. However, there was no significant relationship between strain and IMT. The relationships between risk factors for atherosclerosis and mechanical forces and their relating parameters viscosity, arterial dimension, and blood velocity are summarized in Table 3. Blood pressure, HDL cholesterol, triglyceride, fasting blood glucose, and smoking were risk factors with a specific association with mechanical forces.

The cumulative effect of risk factors on mechanical forces is illustrated in Figure 2. Shear stress showed a significant negative relationship and circumferential wall tension showed a significant positive relationship with the number of risk factors. However, this dependency was not observed for strain. Stepwise regression analysis further revealed that the number of risk factors was significantly associated with mechanical forces independently of IMT (Table 4).

Discussion

Shear stress participates in the modulation of endothelial function. Recent studies both in vitro and in vivo indicate that low shear stress is related to atherosclerosis. Stretch also plays a pivotal role in the progression of atherosclerosis. The molecular mechanisms as well as clinical observations suggest that a high stretch stimulus is related to atherosclerosis. In the present study the relationship between mechanical forces and carotid atherosclerosis was evaluated in patients with risk factors, including hypertension, dyslipidemia, and/or diabetes. In this population, we confirmed previous findings that shear stress showed a significant negative correlation and circumferential wall stress showed a significant positive correlation with IMT.

The association between several risk factors and carotid atherosclerosis has been extensively studied. The relationship between risk factors and mechanical forces has also been investigated in a few studies. Shear stress has shown no change or was decreased in non–insulin-dependent diabetes mellitus. In previous studies we observed reduced shear stress in hypertensive patients as well as in subjects with left ventricular hypertrophy. In the present study we further observed that the associations with mechanical forces were different among risk factors. SBP showed a significant negative correlation with shear stress and strain. HDL cholesterol showed a significant positive correlation with shear stress and a negative correlation with wall tension. Fasting blood glucose was negatively associated with shear stress, while smoking showed a significant negative association with shear stress and a positive association with wall tension. Furthermore, the findings in the present study that the accumulation of risk factors precipitated alteration of mechanical stresses and that the number of risk factors was independently associated with mechanical forces indicate the additive effect of risk factors on mechanical forces.

As underling mechanisms, the association between risk factors and components of the mechanical forces viscosity,
dimension, and blood velocity was also investigated. The association between structural and functional parameters of the CCA with risk factors for atherosclerosis has been reported. CCA diameter has been shown to be related to risk factors for atherosclerosis, including hypertension and smoking.\(^{19,20}\) We also observed reduced blood flow velocity in hypertensive patients.\(^{21}\) The reduced shear stress in an insulin-dependent diabetes mellitus patients has been shown to be a consequence of both decreased flow velocity and larger carotid diameter, by the same method as that used in the present study.\(^{6}\) It was also shown that carotid diameter increases in compensation for increased wall thickness.\(^{22}\) In the present study we further observed that the association between risk factors and the components of mechanical forces was significantly different among risk factors. Since shear stress is the direct consequence of carotid diameter, blood viscosity, and flow velocity, and wall tension is the product of blood pressure and carotid diameter, the alteration of these components associated with risk factors influences the mechanical forces. These findings indicate that alteration of the mechanical forces coincides with morphological and functional changes observed in response to the risk factors for atherosclerosis.

As the stretch stimulus, in vitro studies have investigated the effect of expansion of endothelium and vascular smooth muscle cells cultured on an elastic membrane mounted in a stretch device.\(^{1,2,14,15}\) Clinically, circumferential wall tension obtained by Laplace’s law was used as the stretch stimulus in vivo.\(^{7}\) Although circumferential wall stress dilates arteries, mechanical force evaluated in an in vivo study is actually different from stretch. Furthermore, Dobrin\(^{3}\) showed that medial thickening occurred in response to circumferential deformation by using a band to narrow the carotid artery proximal to the vein graft. This finding suggests that the effect of circumferential wall tension and strain may be different in vivo. In the present study we did not find any association between strain and carotid atherosclerosis, suggesting that wall tension was more closely related to atherosclerosis than circumferential deformation in vivo.

Although we evaluated the hemodynamic forces in the carotid artery, the findings in the present study may be expanded to other arteries. The parallel alteration of the vessel diameters has been reported in carotid arteries, iliac arteries, femoral arteries, and popliteal arteries as a common pathological response in early atherosclerosis.\(^{23}\) Brachial arterial diameter has also been reported to be larger in diabetic patients\(^{24}\) and hypertensive patients\(^{25}\) than in control subjects. These findings indicate that risk factor–dependent alteration of hemodynamic forces may be a generalized phenomenon in systemic arteries.

Pulse pressure has been shown to be the major determinant of cardiovascular risk in elderly hypertensive subjects.\(^{26}\) In the present study pulse pressure showed significant associations with mean shear stress as well as mean circumferential wall tension. Since stiffness of the arteries underlies widening of pulse pressure,\(^{27}\) these findings may indicate that stiffness of the artery could be associated with the alteration of hemodynamic forces. In stiffer arteries SBP is augmented by early wave reflection due to the fast traveling of pulse wave, resulting in the increase in circumferential wall tension. Stiffer arteries have also been shown to be associated with reduced blood flow velocity in the diastole.\(^{21}\) These changes associated with stiffer arteries could further reduce shear stress.

Gnasso et al\(^{5}\) investigated wall shear stress in the carotid artery with plaque. They found that wall shear stress is lower in the carotid arteries where plaques are present than in plaque-free arteries. They concluded that shear stress in the CCA would influence downstream parameters. In the present study 13 plaques were observed in the right CCAs. Although all of those measured for determination of blood flow velocity were located downstream, it is also conceivable that the presence of plaque downstream could influence hemodynamic parameters upstream. It has also been reported that blood velocity and blood flow in the CCA were reduced in the presence of stenosis of the internal carotid artery.\(^{28}\) These

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**TABLE 3. Correlation Coefficients Between Risk Factors and Mechanical Forces and Related Parameters in Total Population**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean Viscosity</th>
<th>Diastolic Diameter</th>
<th>Mean Blood Velocity</th>
<th>Mean Shear Stress</th>
<th>Mean Wall Tension</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>-0.19*</td>
<td>...</td>
<td>-0.17*</td>
<td>-0.32‡</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>0.32‡</td>
<td>0.31‡</td>
<td>...</td>
<td>0.22*</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Body mass index</td>
<td>0.29‡</td>
<td>0.35‡</td>
<td>...</td>
<td>0.43‡</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>DBP</td>
<td>0.18*</td>
<td>0.45‡</td>
<td>-0.25‡</td>
<td>-0.28‡</td>
<td>...</td>
<td>-0.19*</td>
</tr>
<tr>
<td>DBP</td>
<td>0.19*</td>
<td>0.33‡</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Pulse pressure</td>
<td>...</td>
<td>0.37‡</td>
<td>-0.20*</td>
<td>-0.33‡</td>
<td>0.53‡</td>
<td></td>
</tr>
<tr>
<td>Total cholesterol</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>HDL cholesterol</td>
<td>-0.25‡</td>
<td>0.22*</td>
<td>0.22‡</td>
<td>-0.27‡</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Triglyceride</td>
<td>0.19*</td>
<td>0.17*</td>
<td>...</td>
<td>0.219‡</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Fasting blood glucose</td>
<td>0.20*</td>
<td>0.43‡</td>
<td>-0.19*</td>
<td>-0.21*</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Smoking</td>
<td>0.20*</td>
<td>0.43‡</td>
<td>-0.28‡</td>
<td>-0.19*</td>
<td>0.39†</td>
<td></td>
</tr>
<tr>
<td>No. of risks</td>
<td>0.19*</td>
<td>0.63‡</td>
<td>-0.34‡</td>
<td>-0.45‡</td>
<td>0.58‡</td>
<td></td>
</tr>
</tbody>
</table>

*\(^{P<0.05}, †^{P<0.01}, ‡^{P<0.001}\).*
findings suggest that the presence of plaque may influence hemodynamic parameters in addition to the risk factors discussed in this study.

Although the methods used in the present study have been reported in previous studies,4–9 there are several limitations of an indirect estimation of hemodynamic parameter. The rationale for the poiseuillean parabolic model of blood flow velocity distribution is based on the assumption of laminar blood flow in the CCA. We could not eliminate the possibility that the presence of plaque, even downstream, may interfere with laminar blood flow. Pulse pressure and SBP significantly increase from the central to the peripheral arteries.29 Since we calculated systolic wall tension using brachial SBP, it is possible that we overestimated systolic wall tension, especially in those of younger age with tall stature.30

In summary, risk factors for atherosclerosis were significantly associated with alteration of mechanical forces. The accumulation of risk factors caused further deterioration of mechanical forces independent of carotid atherosclerosis. These findings indicate that consequent alteration in mechanical forces associated with risk factors could be an underlying local mechanism for the progression of atherosclerosis.

Acknowledgments

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References

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