Background—Experiments under controlled flow conditions indicate that the binding of von Willebrand factor (vWF) to platelet glycoprotein (GP) Ibα and integrin αIIBβ3 (GP IIb/IIIa complex) is crucial for aggregation at elevated shear rates. We have tested how the plasma of patients with acute myocardial infarction affects this process.

Methods and Results—Citrated plasma was obtained from 18 patients with acute myocardial infarction within 6 hours from the onset of symptoms and from 26 control subjects with chest pain syndrome without evidence of ischemia. Aggregation of normal platelets at high shear rates was significantly greater in the presence of patient plasma and was inhibited by both anti-GP Ibα and anti-αIIBβ3 monoclonal antibodies. The observed values (mean±SD) were 47.6±17.8% versus 30.1±9.9% at 10 800 s⁻¹ (P<0.01) and 32.9±14.1% versus 17.5±9.5% at 7200 s⁻¹ (P<0.01), respectively, and were positively correlated with plasma vWF antigen levels and ristocetin cofactor activities. In contrast, at the lower shear rate of 1200 s⁻¹, aggregation was similar in the presence of control or patient plasma and was not inhibited by the anti-GP Ibα antibody. Both vWF antigen and platelet aggregation decreased 2 weeks after the onset of myocardial infarction.

Conclusions—Shear-induced platelet aggregation is enhanced in plasma in the presence of acute myocardial infarction, apparently as a result of increased vWF concentration. This may contribute to the onset of acute coronary artery thrombosis and early reocclusion after reperfusion treatment. (Circulation. 1999;99:608-613.)

Key Words: platelets ■ von Willebrand factor ■ glycoproteins ■ thrombosis

Unstable angina and acute myocardial infarction are often associated with the development of fresh platelet-rich thrombi, suggesting that platelet adhesion and aggregation, as well as fibrin deposition, are pathogenetic factors in ischemic heart disease. Moreover, reperfusion treatment by thrombolysis or angioplasty may reduce in-hospital mortality and preserve left ventricular pump function in patients with acute myocardial infarction, but its efficacy is limited by the occurrence of thrombotic reocclusion after revascularization. Animal studies and clinical observations suggest that increased thrombin activity and platelet aggregation, both amenable to control by pharmacological agents, may be involved in the occurrence of reocclusion. Thus, understanding the mechanisms that regulate platelet reactivity may lead to better prevention and treatment of ischemic heart disease. Fluid dynamic forces may be relevant in this regard, because blood flow through stenotic atherosclerotic arteries results in extremely elevated shear rates. Under such hemodynamic conditions in ex vivo experiments, the adhesive protein von Willebrand factor (vWF) and its 2 membrane receptors, glycoprotein (GP) Ibα and integrin αIIBβ3 (GP IIb/IIIa), are crucial for platelet aggregation. Moreover, epidemiological studies have shown a positive correlation between plasma vWF levels and incidence of heart disease caused by arterial thrombosis. All these results suggest that vWF may be involved in the onset of coronary events, but whether this depends on its effects on the thrombogenic potential of platelets in flowing blood remains to be established.

In the present study, we have found that the plasma of patients with acute myocardial infarction significantly augments the aggregation of platelets exposed to high shear rates. Our results suggest that increased vWF concentration, possibly in association with other humoral factors, may be responsible for this phenomenon and imply that vWF-dependent shear-induced platelet aggregation may have a causative role in the onset of acute coronary thrombosis leading to myocardial infarction or reocclusion after reperfusion treatment.

Methods

Patient Selection

Eighteen patients admitted to Tokai University Hospital in Kanagawa, Japan, within 6 hours of the onset of acute myocardial...
TABLE 1. Clinical Characteristics of Enrolled Patients

<table>
<thead>
<tr>
<th>Case</th>
<th>Patient</th>
<th>Age, y</th>
<th>Location and Severity of Coronary Artery Disease</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66</td>
<td>LAD #7, 100%</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>49</td>
<td>LAD #7, 99%</td>
<td></td>
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<tr>
<td>3</td>
<td>87</td>
<td>LMT #5, 99%</td>
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<tr>
<td>4</td>
<td>82</td>
<td>LAD #7, 99%</td>
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<tr>
<td>5</td>
<td>47</td>
<td>RCA #2, 100%</td>
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</tr>
<tr>
<td>6</td>
<td>39</td>
<td>LAD #7, 100%</td>
<td></td>
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<tr>
<td>7</td>
<td>62</td>
<td>LAD #7, 100%</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>54</td>
<td>LAD #6, 100%</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>64</td>
<td>RCA #2, 100%</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>59</td>
<td>RCA #1, 100%</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>56</td>
<td>LCx #13, 100%</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>58</td>
<td>RCA #1, 100%</td>
<td></td>
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<tr>
<td>13</td>
<td>39</td>
<td>LAD #7, 100%</td>
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<td>LAD #6, 100%</td>
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<tr>
<td>18</td>
<td>56</td>
<td>LCx #13, 100%</td>
<td></td>
</tr>
</tbody>
</table>

LAD indicates left anterior descending artery; LMT, left main trunk; RCA, right coronary artery; and LCx, left circumflex coronary artery.

Complete occlusion of coronary artery is indicated as 100%; >90% stenosis in luminal diameter with delay in coronary arterial opacification is indicated as 99%.

infarction symptoms, who had not received medications known to interfere with platelet function, gave written informed consent to enter the study. The characteristics of their coronary artery disease are summarized in Table 1. The diagnosis was based on typical chest pain resistant to nitroglycerin, ECG ST-segment elevation in ≥2 leads with or without Q-wave formation, and significant increase in plasma cardiac enzymes, including creatine phosphokinase (CPK) and lactate dehydrogenase. The MB isozyme of CPK, a relatively specific indicator of myocardial damage, was elevated by 5% in all enrolled patients. Emergency coronary angiography and subsequent revascularization by balloon angioplasty were performed in all cases.

Sample Preparation
Blood samples were drawn from the femoral vein with a 19-gauge needle before any medical treatment and transferred from a plastic syringe into a tube containing 10% vol of 3.8% trisodium citrate (pH 7.4). Platelet-poor plasma was separated from blood cells by centrifugation at 1500g for 20 minutes and stored at −80°C until used. In 7 cases (patients 11, 12, 14, 15, 16, 17, and 18 in Table 1), plasma for measuring vWF antigen concentration was obtained immediately after reperfusion treatment and then 7 and 14 days after the diagnosis of myocardial infarction. Plasma from normal donors who had not interfered with platelet function was prepared and stored in the same manner. Plasma vWF antigen was also determined in 26 patients (aged 53.1 ± 8.2 years; 18 men and 8 women) who presented with chest pain without evidence of ischemia induced by treadmill exercise. Ten of the 26 control samples were randomly selected for additional determination of the ristocetin cofactor activity of vWF (vWF RCA) and shear-induced platelet aggregation.

Shear-Induced Platelet Aggregation
The influence of patient and control plasma on shear-induced aggregation of normal platelets in the absence of exogenous agonists was tested in an optically modified cone-and-plate viscometer.

Platelets were prepared before each experiment from the same 36-year-old normal male volunteer with blood group O. Platelet-rich plasma (PRP) was prepared by centrifugation at 120g for 15 minutes and adjusted to a platelet count of 4 × 10^9/μL by addition of homologous platelet-poor plasma obtained after further centrifugation of blood at 1500g for 15 minutes. The effect of acute myocardial infarction plasma on platelet aggregation was tested in mixtures of 200 μL of normal PRP and 200 μL of patient or control platelet-poor plasma. The effect of exogenously added purified human vWF was tested in the mixture of 200 μL of normal PRP, 180 μL of control platelet-poor plasma, and 20 μL of HEPES-NaCl solution (pH 7.4) with or without vWF to achieve a final concentration of 15 or 30 μg/mL. Aggregation was evaluated at 10 800 s⁻¹ (108 dyne/cm²) and 7200 s⁻¹ (72 dyne/cm²), shear rates at which it is dependent on vWF, as well as at 1200 s⁻¹ (12 dyne/cm²), in which case it is mediated by fibrinogen. Shear stress was calculated assuming a viscosity of 1 centipoise because no red cells were present in the experimental mixtures. We calculated the extent of platelet aggregation from the changes in light transmittance through the sample, recorded at 1-second intervals, using the Lambert-Beer equation.

Monoclonal Antibodies
LJ-Ib1, an anti-GP Ibα murine IgG1, inhibits vWF binding and platelet aggregation at high shear rates but not agonist-induced aggregation at lower shear rates. LJ-CP8, a complex specific anti-α₃β₁ murine IgG1, inhibits fibrinogen and vWF binding to activated platelets as well as shear-induced and agonist-induced platelet aggregation.

Plasma Antigen Level, RCA, and Multimeric Distribution of vWF
The plasma concentration of vWF antigen was measured by enzyme immunoassay in 18 acute myocardial infarction and 26 control plasma samples. RCA was measured by a fixed platelet ELISA method in all myocardial infarction and in 10 randomly selected control plasma samples. The multimeric distribution of vWF was analyzed by SDS-agarose gel electrophoresis in 10 myocardial infarction (patients 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 in Table 1) and 2 control samples. vWF antigen level and RCA were also measured serially in 7 selected cases of myocardial infarction, as described above.

Statistics
The null hypothesis between control and patient results was evaluated by use of the Student t test for unpaired samples. Serial data were evaluated by ANOVA with the Newman-Keuls multiple comparison procedure. A P value of <0.05 was considered statistically significant.

Results
Platelet Aggregation Under Shearing Flow
Platelet aggregation induced by shear rates of 10 800 and 7200 s⁻¹ but not 1200 s⁻¹ was enhanced in the presence of plasma from several patients with acute myocardial infarction compared with control plasma (Figure 1). The mean ± SD of the maximum extent of aggregation at 10 800 s⁻¹ was 47.6 ± 17.8% with patient plasma and 30.1 ± 9.9% with control plasma; at 7200 s⁻¹, the respective values were 32.9 ± 14.1% and 17.5 ± 9.5%. The difference was significant at the 2 higher shear rates (P < 0.01) but not at 1200 s⁻¹ (Table 2). In spite of the clear group separation, some individual control and patient values overlapped (Figure 2). Not only the extent but also the maximum rate of aggregation at the higher shear rates was significantly greater in the presence of patient than control plasma, more so at 7200 than at 10 800 s⁻¹ (Table 2). In fact, the maximum rate of aggregation at 7200
was 33% of that at 10 800 s$^{-1}$ with control plasma but essentially identical with acute myocardial infarction plasma (Table 2). These results indicate that the latter condition lowered the threshold for rapid platelet response to high shear stress. At both 10 800 and 7200 s$^{-1}$, aggregation with either control or patient plasma was inhibited by antibody LJ-Ib1 (Figure 1), which is in agreement with the known role of vWF binding to GP Ib$^\alpha$ in the initiation of shear-induced aggregation. Inhibition, although less pronounced, was also observed with the anti-α$\alpha_\text{IIb}\beta_3$ antibody LJ-CP8 (Figure 1). In contrast, LJ-Ib1 had no effect at 1200 s$^{-1}$, whereas LJ-CP8 caused complete inhibition (Figure 1), which supports the concept that aggregation induced by this relatively low shear is mediated by fibrinogen binding to α$\alpha_\text{IIb}\beta_3$ and is independent of vWF interaction with GP Ib$^\alpha$.12,18

Plasma Concentration of vWF
Concentrations of vWF antigen and RCA were significantly higher in patients with acute myocardial infarction than in normal controls (Figure 3). Larger vWF multimers were relatively increased in 3 patients (patients 1, 7, and 8) but not in the remaining 7 (data not shown). The extent of aggregation at 10 800 and 7200 s$^{-1}$ but not at 1200 s$^{-1}$ was significantly correlated with the plasma levels of vWF antigen and RCA in the patients (Figure 4), which suggests a causative role for vWF in the observed phenomenon. Accordingly, platelet aggregation at 10 800 and 7200 s$^{-1}$ but not at 1200 s$^{-1}$ was enhanced by the addition of purified human vWF to normal PRP (Figure 5). Plasma vWF antigen (Figure 6) and shear-induced aggregation (Figure 7) did not change significantly after successful revascularization, which suggests that these parameters are not strictly a reflection of platelet activation or endothelial cell damage in the affected coronary arteries. However, a significant ($P<0.02$) difference in serial measurements of vWF antigen was found in the patients, with lower values at 14 days after the onset of myocardial infarction than before or immediately after PTCA (Figure 6; $P<0.01$ in either case). Platelet aggregation at high shear rate (Figure 7) was also decreased by 14 days after the onset of acute myocardial infarction.

Discussion
Our results indicate that the plasma of patients with acute myocardial infarction can enhance shear-induced platelet aggregation, and vWF appears to be the relevant if not essential determinant of this response, possibly contributing to the onset of coronary thrombosis and early reocclusion of recanalized arteries. Elevation of plasma vWF from any cause may be accompanied by heightened shear-induced aggregation, as shown in the present study by the addition of purified vWF to normal plasma or in patients with effort angina after treadmill exercise.24 However, plasma vWF levels may become a risk factor for arterial thrombosis only when altered.
hemodynamic conditions at the site of severe coronary artery stenosis result in abnormally high shear rates. Such conditions may arise suddenly from the progression of atherosclerotic plaques restricting the arterial lumen beyond a critical point, possibly with the contribution of vasospasm, and may be precipitated by the exposure of thrombogenic surfaces after plaque rupture. Thus, enhanced vWF-dependent platelet aggregation is only 1 of several possible coincidental factors involved in the onset of myocardial infarction, but it may be a prevailing cause of acute thrombotic occlusion in the context of chronic coronary artery disease. The evidence provided herein that abnormally increased vWF concentra-
Enhanced Shear-Induced Platelet Aggregation in AMI

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Figure 7. Shear-induced platelet aggregation in presence of plasma from a patient with acute myocardial infarction before and at different times after reperfusion treatment with PTCA. Aggregation occurring at shear rates of 10 800 and 7200 s⁻¹ but not at 1200 s⁻¹ was enhanced in presence of acute myocardial infarction plasma compared with control, and there was no difference whether the sample had been obtained before or immediately after successful reperfusion treatment. Aggregation was lower in patients 14 days after onset of myocardial infarction than in the acute phase. Figure shows results of 1 experiment with patient 11 (Table 1), but the findings were similar in 2 additional patients (patients 14 and 16), except that with plasma from patient 16, the extent of aggregation 14 days after onset of myocardial infarction was even less than with control plasma.

Recent development of specific antiplatelet agents, including the chimeric 7E3 antibody, have proven effective in the prevention of acute coronary artery occlusion after angioplasty.9,35 These agents inhibit not only fibrinogen but also vWF binding to activated α₃β₃ and subsequent shear-induced platelet thrombus growth.36 Although it is generally maintained that fibrinogen is the exclusive mediator of platelet aggregation initiated by exogenous chemical agonists,37 a more careful consideration of the effects of fluid dynamic forces has revealed that vWF may provide a major contribution to interplatelet cohesion during thrombus formation.10–12,38,39 Such a conclusion is supported by epidemiological studies that have linked vWF, as well as fibrinogen, to the risk of developing acute coronary events.14,15 Thus, it seems reasonable to propose that vWF may be one of the ligands involved in mediating platelet aggregation in blood flowing with high shear rates. Experimental evidence in this regard has been obtained with the demonstration that even after strong activation by exogenous chemical agonists, fibrinogen binding by itself is not sufficient to support interplatelet contacts with adequate adhesive strength to oppose high shear stress.40 In such conditions, which may be of paramount importance in the arterial circulation, particularly in the presence of stenosis, the role of vWF in mediating optimal platelet aggregation appears to be essential, notably with the involvement not only of GP Ibα but also of α₃β₃.40 Consequently, the clinical effects of pharmacological inhibitors of α₃β₃ function may depend on blocking platelet binding of vWF as well as fibrinogen. A conclusive evaluation of this hypothesis in the clinical setting must await the availability of drugs that selectively inhibit the interaction of vWF with platelets.

Acknowledgments

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References


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