Functional Significance of Adenosine 5′-Diphosphate Receptor (P2Y$_{12}$) in Platelet Activation Initiated by Binding of von Willebrand Factor to Platelet GP Ibα Induced by Conditions of High Shear Rate

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Background—The role of the adenosine 5′-diphosphate receptor P2Y$_{12}$ in platelet activation initiated by the von Willebrand factor (VWF)–GP Ibα interaction under high shear rate was investigated.

Methods and Results—Blood samples were obtained from 11 donors. Shear-induced platelet aggregation was detected by optically modified cone-plate viscometer. Shear-induced VWF binding, P-selectin expression, and microparticle release were detected by flow cytometry. Platelet interaction with immobilized VWF was also investigated by parallel-plate flow chamber equipped with epifluorescent videomicroscopy. Effects of a selective P2Y$_{12}$ antagonist AR-C69931 MX were tested. AR-C69931 MX inhibited shear-induced platelet aggregation in a dose-dependent manner, achieving the maximum inhibition at 100 nmol/L. The extent of aggregation after exposure to a shear rate of 10 000 s$^{-1}$ for 6 minutes in the presence of 100 nmol/L AR-C69931 MX was 32.4±8.2% (mean±SD), which was significantly lower than the value in the controls of 69.7±9.6% (P<0.01). The inhibiting effects of AR-C69931 MX were reversed by exogenous addition of adenosine 5′-diphosphate. Shear-induced VWF binding and P-selectin surface translocation, which occurred in 4696±911 and 5964±784, respectively, of 10 000 measured platelets, was also inhibited by AR-C69931 MX (100 nmol/L) to 1948±528 and 2797±718, respectively (P=0.0018 and P=0.0009). Microparticle release was similarly inhibited. In a flow chamber experiment, firm platelet attachment on immobilized VWF was inhibited by AR-C69931 MX, whereas transient interaction was not influenced. All the above reactions were completely inhibited by blocking VWF–GP Ibα interaction.

Conclusions—We have demonstrated that the stimulation of P2Y$_{12}$ is involved in platelet activation initiated by the binding of VWF to GP Ibα induced by a high shear rate. (Circulation. 2002;105:2531-2536.)

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

Recent investigations have revealed that the antiplatelet effects of thienopyridine antiplatelet agents such as ticlopidine and clopidogrel depend on the specific and irreversible inhibition of platelet adenosine 5′-diphosphate (ADP) receptors coupled with Gi/adenylate cyclase (P2TAC).1 Recently cloned as P2Y$_{12}$,2 by their active metabolites.3 Although 3 different ADP receptors mediating different cellular reactions of platelets have been cloned so far (eg, P2X$_{1}$, which mediates calcium influx, P2Y$_{1}$, which mediates intracellular calcium mobilization, and P2Y$_{12}$, a Gi-coupled receptor mediating the action of adenylyl cyclase2,4,5 and other more complex signaling that has yet to be clarified,6,7), understanding the role played by P2Y$_{12}$ receptors is particularly important since large-scale randomized clinical studies have shown the effectivenss of thienopyridine antiplatelet agents in preventing arterial thrombotic disease.8,9 Many reports indicate that P2Y$_{12}$ stimulation by exogenously added ADP is crucial for platelet activation and aggregation in vitro.2,4,5,10,11 However, the important issue—why in vivo arterial thrombosis was prevented by its inhibition—is still not fully understood.

Recent investigation revealed that von Willebrand factor (VWF) and its interaction with platelet receptor proteins GP Ibα and GP IIb/IIIa played an important role in the onset of platelet thrombosis at sites exposed to high shear rates.12-14 In this study, we attempted to clarify the role of the P2Y$_{12}$ receptor inhibition in VWF-mediated platelet activation and aggregation under high shear stress by using the specific P2Y$_{12}$ antagonist AR-C69931 MX.15

Methods

Preparation of Platelet Samples

Platelet-rich plasma was separated by centrifugation of blood specimens anticoagulated by citrate (0.38%), obtained from healthy adult

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donors who abstained from drugs known to interfere with platelet function (such as nonsteroidal antiinflammatory drugs) for at least 4 weeks. Additional blood samples obtained for the flow experiments were anticoagulated by the specific antithrombin agent Argatroban (Mitsubishi Kagaku Co) at a final concentration of 100 μmol/L.

Shear-Induced Platelet Aggregation, VWF Binding to Platelets, and Platelet Activation

Platelet aggregation under a selected shear rate can be measured with the use of an optically modified cone-plate viscometer as described previously.14,16,17 Effects of AR-C69931 MX was tested at 10 800 s⁻¹ because a previous study demonstrated VWF binding with both GP Ibα and GP Ibβ/IIa was required to induce aggregation at that high shear rate.17 Laser light transmittance of the sample was measured continuously while the samples were exposed to a shear field, and the measured light transmittance, which was converted to the level of platelet aggregation based on the Lambert-Beer equation, was stored in a computer (PC-9800CX, NEC).17

Shear-induced VWF binding and subsequent activation with P-selectin surface translocation was detected by flow cytometry with FITC-conjugated specific anti-VWF (LJ-C3, provided by Dr Zaverio M. Ruggeri from the Scripps Research Institute)18 and anti-P-selectin (WGA1) monoclonal antibody.19 Two other agents, FITC-conjugated anti–GP Ibα (LJ-P3, also provided by Dr Zaverio)18 and FITC-conjugated Annexin V, which bind to phospholipid-rich procoagulant surfaces,20 were used to detect platelet-derived microparticles. LJ-P3 was used because it did not compete with VWF binding to GP Ibα.21 Shear-induced microparticle release was calculated as the difference between samples exposed to the shear forces and control samples that were not exposed.

Platelet Interaction With Immobilized VWF Under Flow Conditions

Human purified VWF was immobilized on glass coverslips (Corning, Inc; 24 × 50 mm) in a parallel-plate flow chamber, as described previously.20,21 Then, whole blood containing platelets rendered fluorescent by mepacrine was pumped through the chamber with a syringe pump at a constant flow rate to achieve a wall shear rate of 1500 s⁻¹. Platelets interacting with immobilized VWF were visualized under an inverted-stage epifluorescence videomicroscope equipped with a 480-nm excitation light source (DM IRB, 1RB-FLUO, Leica).22 The microscopic images were digitized on-line with a photosensitive color CCD camera (L-600, Leica) and stored as digital images in a personal computer (Power Macintosh G3, Apple Co, Ltd). The effects of AR-C69931 MX on platelet-VWF surface interaction was qualitatively demonstrated by overlaying 60 consecutive frames of the video images (corresponding to 2 seconds), so that firmly attached platelets that did not move appeared as thick images, whereas moving (eg, rolling) platelets, which appeared in only some of the frames, appeared as thinner images. The movement of every single platelet appearing in the consecutive image frames was quantified.

Reagents Used in Experiments

AR-C69931 MX, a specific inhibitor of P2Y₁₂, was kindly provided by AstraZeneca R&D Charnwood (Loughborough, Leicestershire, England). The basic characteristics of the material have been described elsewhere.15 FITC-conjugated PAC-1 and its binding to ADP-activated GP Ibβ/IIa were detected by flow cytometry.24 This assay was used to characterize AR-C69931 MX. LJ-Ib1, the antibody blocking the binding of VWF to GP Ibα, was also kindly provided by Dr Zaverio. This antibody is known to block shear-induced binding of VWF to GP Ibα to generate a negative control.18

Statistical Analysis

All numerical data are expressed as mean ± SD unless otherwise specified. The effect of various concentrations of AR-C69931 MX on platelet aggregation and activation was tested by 1-way ANOVA. Differences between two groups of data were compared by Fisher analysis. Statistical significance of the difference between two groups of data was tested by Student’s paired t test. A value of P < 0.05 was considered to be statistically significant.

Results

Effects of AR-C69931 MX on Shear-Induced Platelet Aggregation

AR-C69931 MX inhibited shear-induced platelet aggregation in a dose-dependent manner at concentrations >5 nmol/L (Figure 1), with the maximum inhibition achieved at 100 nmol/L. The extent of aggregation after exposure to a shear rate of 10 800 s⁻¹ for 6 minutes in the presence of 100 nmol/L AR-C69931 MX was 32.4 ± 8.2% (mean ± SD), which was significantly lower than that in the absence of the agent of 69.7 ± 9.6% (P < 0.01). At relatively low concentrations, that is, <1 nmol/L, disaggregation occurred, although the maximum extent of aggregation was not influenced. The aggregation observed under the tested shear rate was mediated by the interaction of VWF with GP Ibα, since it was completely inhibited by an antibody that would block this interaction.
The inhibiting effect of AR-C69931 MX on the shear-induced aggregation was mediated by its competition for the P2Y_{12} receptor with ADP, since its inhibiting effects could be reversed by exogenous addition of ADP, as shown in Figure 2. Receptor competition between ADP and AR-C69931 MX was confirmed by a simple ADP-induced platelet activation assay, as shown in Figure 3. The inhibitory effects of AR-C69931 MX on ADP-induced platelet activation, as evidenced by the PAC-1 binding, was overcome by addition of extremely high concentrations of ADP.

Effects of AR-C69931 MX on Shear-Induced Platelet Activation

Of 10,000 platelets measured, shear-induced VWF binding and P-selectin translocation occurred in 4296±911 and 5964±784 platelets, respectively (Figure 4). Mean numbers of anti-VWF and anti-P-selectin antibodies binding to single platelets increased from 294.6±49.1 per platelet and 43.4±46.0 per platelet before shearing to 1369.4±318.8 per platelet and 1821±814 per platelet after shearing, respectively (P<0.0015 and P<0.0071, respectively). Platelet-derived microparticles, measured as particles with GP Ibα and those with procoagulant activity detected by annexin V binding, also increased from 1663±1021 and 1023±445 before shearing to 16744±6903 and 9745±3832 after shearing, respectively (P<0.0030 and P<0.022). The shear-induced VWF binding and subsequent platelet activation evidenced by P-selectin surface translocation and microparticle release were inhibited by AR-C69931 MX in a dose-dependent manner (Figure 4). Shear-induced VWF binding, P-selectin surface translocation, and microparticle release were inhibited at 65.9±17.3, 68.5±16.0, and 65.4±11.6 (%), respectively, with 100 nmol/L AR-C69931 MX, whereas 95.4±4.6, 93.5±5.6, and 89.5±9.0 (%) of those reactions could be inhibited by the monoclonal antibody capable of blocking the binding of VWF to GP Ibα (Figure 5). Mean numbers of anti-VWF and anti-P-selectin antibodies binding to single platelets still increased from 233.6±50.0 and 10.7±33.4 before shearing to 463.3±92.1 and 282.1±192.6 after shearing, even in the presence of 100 nmol/L AR-C69931 MX, respectively (P<0.0028 and P<0.020, respectively).

Effects of AR-C69931 MX on Platelet Interaction With Immobilized VWF in Whole Blood Experiments

Firm platelet attachment on immobilized VWF occurring under a wall shear rate of 1500 s⁻¹ was inhibited by AR-C69931 MX at a dose maximally inhibiting shear-
induced platelet aggregation (100 nmol/L), whereas temporally tethering and rolling on VWF surface was not inhibited (Figure 6). Platelets once adhered on the VWF surface in the absence of AR-C69931 MX moved only 0.38±0.35 μm during 2 seconds, whereas they moved 1.64±1.27 μm in the presence of 100 nmol/L AR-C69931 MX (P=0.0021).

**Discussion**

We have demonstrated that >50% of platelet activation and aggregation caused by the interaction of VWF with platelet GP Ibα under conditions of high shear rate in platelet-rich plasma could be inhibited by blocking the action of P2Y12 by AR-C69931 MX. We also demonstrated that firm platelet attachment on immobilized VWF in whole blood, presumably mediated by VWF binding to activated GP Ibβ/IIa, is inhibited by AR-C69931 MX, suggesting the role of P2Y12 in VWF-mediated platelet activation in whole blood, too. These results, along with previously published findings demonstrating the involvement of VWF-mediated platelet thrombosis in animal arterial thrombosis models12,13 or ex vivo human studies,14,16–19,25–28 strongly suggest the importance of P2Y12 stimulation in the process of arterial thrombosis. Our present findings provide experimental evidence explaining the mechanism of in vivo antithrombotic action of P2Y12 inhibition achieved by thienopyridine antiplatelet agents such as ticlopidine and clopidogrel in the absence of exogenous addition of ADP. In addition, our results provide important experimental evidence showing that blocking P2Y12 stimulation by ADP released from platelets abrogates >50% of platelet reaction initiated by VWF–GP Ibα interaction.

Our findings with the specific P2Y12 antagonist AR-C69931 MX on shear-induced platelet activation and aggregation agree with previously published findings describing...
Partial P2Y12 inhibition may cause VWF-mediated aggregation and activation 29–32 whereas the maximum extent of shear-aggregated platelets under high shear rates occurs after approximately half of the platelet reactions initiated by the addition of ADP, strongly suggest that the effects of AR-C69931 MX, both through biochemical binding assays and by pharmacological studies, 15 AR-C69931 MX inhibits an ADP-induced decrease in cAMP but does not influence other cellular reaction induced by ADP increases, such as Ca2+ influx, intracellular mobilization of Ca2+, or ADP-induced shape change in platelets.5 Those results suggested that the effects of AR-C69931 MX on ADP receptors other than P2Y12 were negligible.

In conclusion, we demonstrated that stimulation of the P2Y12 receptor plays an important enhancing role in the process of VWF-mediated platelet activation and aggregation occurring under high shear rates. Platelet-derived ADP and its stimulation of P2Y12 may be a common enhancing system of the platelet response.

There still are obvious methodological limitations in our experimental design that limit the application of our results to a clearer understanding of the mechanism of the in vivo antithrombotic effects of thienopyridine antiplatelet agents. Indeed, although the importance of the VWF-mediated mechanism of platelet thrombosis was demonstrated in animal models of arterial thrombosis,12,13 the contribution of the VWF-mediated mechanism of platelet thrombus formation is still speculative in the case of human arterial thrombosis.26 Thus, our idea that thienopyridine antiplatelet agents prevent in vivo arterial thrombosis through inhibition of VWF-mediated platelet activation and aggregation is still speculative. Further investigations will be required to demonstrate the role of VWF-mediated mechanisms in the process of in vivo arterial thrombosis. The other important limitation of our study is that the involvement of another important contributing factor for a thrombosis coagulant system was not considered. In the setting of thienopyridine antiplatelet therapy, in addition to platelet thrombosis, fibrin formation might also be influenced, since we have demonstrated that platelet-derived microparticles, which are known to be a major source of platelet procoagulant activity,29 could be inhibited by P2Y12 inhibition with the use of AR-C69931 MX.

We used AR-C69931 MX as a specific P2Y12 antagonist. We have demonstrated the competitive effects of AR-C69931 MX and ADP on platelet activation, as evidenced by PAC1 binding, which detects activated GP IIb/IIIa.24 Although at least 3 different subtypes of ADP receptors have been cloned,24 previous studies clearly indicate the nature of the specific inhibition of P2Y12, by AR-C69931 MX, both through biochemical binding assays and by pharmacological studies.15 AR-C69931 MX inhibits an ADP-induced decrease in cAMP but does not influence other cellular reaction induced by ADP increases, such as Ca2+ influx, intracellular mobilization of Ca2+, or ADP-induced shape change in platelets.5 Those results suggested that the effects of AR-C69931 MX on ADP receptors other than P2Y12 were negligible.

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