Platelet Glycoprotein VI Dimerization, an Active Process Inducing Receptor Competence, Is an Indicator of Platelet Reactivity

Stephane Loyau, Benedicte Dumont, Veronique Ollivier, Yacine Boulaftali, Laurent Feldman, Nadine Ajzenberg, Martine Jandrot-Perrus

Objective—The immune receptor homologue glycoprotein VI (GPVI)/Fcγ complex is primarily responsible for platelet activation by collagen. There is growing evidence that optimal binding of GPVI to collagen depends on the assembly of GPVI dimers. The valence of GPVI on resting platelets needs to be clearly established because platelet avidity for collagen would be greater if GPVI is constitutively expressed as a dimer than as a monomer.

Methods and Results—Using a monoclonal antibody (9E18) that preferentially binds to GPVI dimers, we found that GPVI was maintained in a monomeric form on human resting platelets under the control of intraplatelet cAMP concentration. Activation by soluble agonists or von Willebrand factor induced a shift toward GPVI dimerization related to increased platelet adhesion to collagen. A correlation between platelet binding of 9E18 and P-selectin exposure was observed in patients experiencing coronary artery disease, and antagonists of the ADP receptor P2Y12 limited ADP-induced GPVI dimerization.

Conclusion—The rapid assembly of highly competent dimers of GPVI at sites of vascular lesion represents an important step in the sequence of events leading to platelet activation by collagen. GPVI dimers could represent a new marker to analyze platelet reactivity. (Arterioscler Thromb Vasc Biol. 2012;32:00-00.)

Key Words: antiplatelet drugs • collagen • monoclonal antibodies • platelets • glycoprotein VI

Platelet adhesion at sites of vascular damage is required for normal hemostasis. Circulating platelets adhere to proteins of the subendothelial matrix exposed by vessel injury in a process involving several receptors. Collagen fibers are highly thrombogenic, and the platelet glycoprotein VI (GPVI) predominantly mediates collagen-induced platelet responses.

GPVI is a platelet-specific receptor of the immunoglobulin (Ig) superfamily containing 2 extracellular Ig domains, a single transmembrane domain, and a short cytoplasmic tail.1–3 GPVI shares with other receptors of the same family the particularity that the extracellular ligand-binding domain and the intracellular signaling domain are on separate subunits. GPVI signals through the noncovalently associated immune receptor adaptor FcRγ.4 The receptor is assembled via a transmembrane interaction between Asp11 in the FcRγ homodimer and Arg273 of GPVI. On stimulation, the Tyr residues of the immunoreceptor tyrosine-based activation motif of FcRγ are phosphorylated in an early, obligatory event triggering the signaling cascade.

There is growing evidence that optimal binding of GPVI to collagen depends on the formation of GPVI dimers at the platelet surface. Miura et al.3 using recombinant proteins, were the first to report that collagen binds to the dimeric form but not to the monomeric form of GPVI and that only the former was able to inhibit collagen-induced platelet activation. Crystallographic data showing dimerization of GPVI ectodomains,6 studies using synthetic peptides with differentially spaced GPVI binding motifs to activate the receptor in platelets,7 and studies using chemical cross-linking agents8 have strongly reinforced the notion that GPVI functions as a dimer. However, the valence of GPVI on resting and on activated platelets is still a matter of debate. It was recently proposed that at least some copies of GPVI may exist in a dimeric conformation at the surface of resting platelets.9 The extent of GPVI dimerization is important to determine because it is expected that platelet avidity for collagen would be greater if GPVI was constitutively expressed as a dimer than as a monomer.

We have obtained an anti-human GPVI monoclonal antibody 9E18 that binds to dimeric GPVI with an affinity at least 200-fold higher than to monomeric GPVI. Using 9E18, we provide evidence that most of GPVI is maintained in a monomeric form on resting platelets under the control of intraplatelet cAMP and that GPVI dimerization occurs in

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response to soluble agonists and to von Willebrand factor (vWF)-induced platelet activation. Interestingly, in a population of coronary artery disease (CAD) patients, a good correlation between 9E18 binding and P-selectin exposure was observed. Furthermore, ADP-induced 9E18 binding to platelets was prevented in patients treated by thienopyridines. In conclusion, binding of 9E18 to platelets is an indicator of GPVI dimerization and could represent a new biomarker of early platelet reactivity and responsiveness to P2Y12 antagonists.

Materials and Methods
Detailed methods available in the Supplemental Data, available online at http://atvb.ahajournals.org.

Antibodies
The anti-human GPVI monoclonal antibodies 3J24 and 9E18 were obtained as previously described.2-10 They are not activating antibodies, as purified IgGs do not trigger P-selectin exposure on platelets. 3J24 and 9E18 bind to different epitopes.10 The 9E18 IgG is able to inhibit GPVI binding to collagen, but its Fab is far less inhibitory than the 9O12 Fab on collagen-induced platelet activation.2-11

Reagents
Collagen from equine tendon (Horn collagen) was from Nycomed (Munich, Germany). Convulxin was purified from the venom of Crotalus durissus terrificus.13 Recombinant soluble GPVI was obtained as the extracellular domain of human GPVI fused to the Ig domain of human IgG (GPVI-Fc that is dimeric)1 or fused to a poly-His tag (GPVI-His that is monomeric). Their K_Dapp for collagen were respectively 1.13 ± 0.03 μmol/L (5 ± 0.2 nmol/L) and 14.7 ± 3.3 μmol/L (270 ± 54 nmol/L), in agreement with published data.5,14 Monomeric GPVI was also obtained by reduction of GPVI-Fc.

Binding Assays Using Purified Proteins
Experiments were conducted mainly as previously described.14 Increasing amounts of purified GPVI-Fc and GPVI-His were incubated in 9E18-coated wells and detected using horseradish peroxidase–coupled anti-human IgG and anti-6×His, respectively.

Isolation of Platelets
Blood was obtained from healthy volunteers who had not taken medication for 10 days, after full informed consent was obtained according to the Declaration of Helsinki. Platelet-rich plasma (PRP) and platelet poor plasma were obtained by centrifugation of citrated blood. Alternatively, blood was collected on acid-citrate-dextrose anticoagulant to prepare washed platelets as previously reported.15

Platelet Adhesion and Activation
Platelet adhesion to immobilized collagen in static conditions was measured as described.11 Platelets activated by ADP, TRAP, epinephrine, or phorbol 12-myristate 13-acetate (PMA) were analyzed by flow cytometry after incubation with fluorescein isothiocyanate–coupled anti-GPVI or P-selectin antibodies. Alternatively, shear-induced platelet activation was performed as previously described.16 Phosphorylation of vasodilator–stimulated phosphoprotein was measured by quantitative flow cytometry. Resistance to clopidogrel was defined by a P2Y12 reactivity ratio >50%.17

Immunoblotting
Proteins from whole platelet lysates were separated by electrophoresis in SDS-polyacrylamide gels and analyzed by immunoblotting using anti-GPVI antibodies and secondary horseradish peroxidase–coupled IgG.3

Patients
Blood samples were obtained from a cohort of patients with CAD referred to the department of cardiology of Bichat hospital for percutaneous coronary intervention (BIOCORE-2 study; clinical trial registration: http://clinicaltrials.gov/ct2/show/NCT01186666?term=NCT01186666&rank=1). The study complies with the Declaration of Helsinki and was approved by the institutional ethics committee. All of the patients provided written informed consent. The patients were treated with dual antiplatelet therapy consisting of aspirin and an antagonist of the P2Y12 receptor, at the discretion of the cardiologist. Blood was drawn on 0.109 mol/L citrate the day after percutaneous coronary intervention. Fluorescence-activated cell sorting analysis was performed on PRP prepared less than 1 hour after blood sampling using fluorescein isothiocyanate–coupled 9E18, 3J24, or anti-P-selectin. Controls were healthy subjects who had taken no medication during the 2 previous weeks.

Statistics
Data were analyzed using PRISM (GraphPad, San Diego, CA). Box plots represent means, minimal, and maximal values. Statistical analysis included the paired Student t test (2-tailed) and the Mann-Whitney test (2-tailed). Correlations were determined using linear regression and Spearman 2-tailed analysis.

Results
9E18 Discriminates Dimeric From Monomeric GPVI
In preliminary experiments, 9E18 IgG were found to bind poorly to GPVI-His (monomeric GPVI) as compared with another anti-GPVI IgG, 3J24. We thus characterized the interaction of dimeric and monomeric GPVI with 9E18 in binding experiments (Figure 1A). Binding of GPVI-Fc to immobilized 9E18 was saturable, allowing calculation of an affinity constant (K_d=0.36 nmol/L). In contrast, GPVI-His hardly bound to 9E18, and saturation was not reached. The best estimated K_d was 78 nmol/L, indicating that the affinity of dimeric GPVI for 9E18 is at least 200-fold higher than the affinity of monomeric GPVI. Furthermore, in competition experiments, soluble GPVI-Fc efficiently inhibited 9E18 binding to immobilized GPVI-Fc, whereas GPVI-His and reduced GPVI-Fc were much less efficient (Supplemental Figure I), confirming that the affinity of 9E18 for monomeric GPVI is far lower than for dimeric GPVI.

Immunoblotting confirmed the poor capacity of 9E18 to detect GPVI-His or reduced GPVI-Fc (Figure 1B and Supplemental Figure I). 9E18 thus permits discrimination between GPVI dimers and monomers.

Binding of 9E18 to Resting Platelets
By flow cytometry, a very low level of 9E18 binding to platelets was observed in whole blood as compared with the level of GPVI labeled by 3J24 (Figure 1C). Interestingly, the basal level of 9E18 binding to platelets increased progressively from whole blood to PRP and washed platelets (2.25±0.7% [n=7], 3.1±2.4% [n=36], and 14±1.6% [n=20] positive platelets, respectively). Furthermore, GPVI was poorly detected using 9E18 on a whole platelet lysate (Figure 1D).

Binding of 9E18 to Activated Platelets
3J34 bound equally well to washed platelets treated with TRAP-1 or ADP as to resting platelets (80±3% and 91±4% respectively).
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s⁻¹ to 7±2% at 4000 s⁻¹ (P<0.05 n=3). Interestingly, although the number of 9E18-positive events was low in the gate corresponding to isolated platelets (2.7±0.4%), it was increased up to 26±7.7% in the gate focused on shear-induced aggregates. Experiments performed with a control mouse IgG ruled out any nonspecific trapping in shear-induced platelet aggregates. When experiments were repeated on washed platelets, the addition of vWF induced a parallel increase in shear-induced platelet aggregation and in the level of 9E18 binding (Figure 3B). P-selectin exposure was also observed on platelet aggregates.

Platelet Adhesion to Collagen

To investigate whether binding of 9E18 was related to the capacity of platelets to interact with collagen, 9E18 binding and GPVI-specific platelet attachment to collagen were measured in parallel, after αIIbβ3, and α5β1 integrins were blocked by the addition of RGDS and the absence of Mg²⁺. A significant linear correlation was observed between binding of 9E18 and the adhesion to collagen (r²=0.87, P=0.0002, n=9), indicating that the conformation of GPVI recognized by 9E18 is favorable for GPVI-dependent platelet adhesion to collagen (Figure 3C).

Mechanisms Leading to Activation-Dependent Changes in GPVI

As binding of 9E18 to platelets was induced by receptor activation, we examined whether it could be induced independently of a cell surface receptor and found that PMA increased the level of 9E18 binding to platelets up to 31.5±4% (P<0.001) (Figure 4). cAMP is established as limiting platelet activation. Adenylate cyclase is inhibited by ADP activation of its receptor P2Y1, and activated by prostacyclin. Whereas ADP increased the binding of 9E18, PGE1 reduced it on washed resting platelets, as well as on TRAP-, ADP-, or PMA-activated platelets (Figure 4A). Forskolin and IBMX induce a receptor-independent elevation of cAMP via the direct activation of adenylate cyclase and the inhibition of phosphodiesterase, respectively. Forskolin plus IBMX (Figure 4A) and even forskolin alone (data not shown) inhibited 9E18 binding to resting, or ADP-, TRAP-, or PMA-activated platelets.

NO donors that increase intraplatelet cGMP concentration are also inhibitors of platelet activation; the NO donor SNAP inhibited 9E18 binding to resting platelets, as well as to TRAP-, ADP-, or PMA-activated platelets (Figure 4A).

The role of endogenous platelet agonists in 9E18 binding to platelets was analyzed. Indomethacin had no effect on the level of 9E18 binding to stimulated platelets, ruling out a role of TXA2. In contrast, apyrase inhibited both ADP- and TRAP-induced binding of 9E18 by 85% and 75%, respectively, indicating that released ADP contributes to GPVI changes. The P2Y₁₂ antagonist 2MeSAMP also inhibited 9E18 binding to ADP- or TRAP-stimulated platelets (data not shown).

Phenylarsine oxide, a reagent that binds to vicinal sulfhydryls and that was previously reported to inhibit GPVI-dependent platelet activation¹⁹,²⁰ is commonly used at low concentrations as an inhibitor of phosphotyrosine phospha-

Shear-Induced Binding of the 9E18 Antibody

The initial interaction of GPIb with vWF, assumed to slow down platelets and to favor GPVI interaction with collagen, was triggered in vitro by high shear stress¹⁸ (Figure 3A). 9E18 binding increased from 3.6±1.6% after 5 minutes at 0 versus 85.5±3%) (Figure 2A). In contrast, binding of 9E18 significantly increased from 14±1.6% to 36.2±7% on TRAP-activated washed platelets and, to a lesser extent (25±5%), on ADP-activated platelets. Both agonists also induced surface exposure of P-selectin. All 9E18-positive events were also P-selectin-positive. There was no aggregation in these conditions. A similar increase in 9E18 binding to stimulated platelets was observed in whole blood (Figure 2B). Epinephrine (0.5 μmol/L) increased the binding of 9E18 to platelets by a factor of 1.5, and this effect was additive with the effect of ADP (data not shown). The IV.3 monoclonal antibody did not prevent 9E18 binding to activated platelets, ruling out a nonspecific binding of 9E18 to Fc antibody did not prevent 9E18 binding to activated platelets, the effect of ADP (data not shown). The IV.3 monoclonal platelets by a factor of 1.5, and this effect was additive with Epinephrine (0.5

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Figure 1. Binding of 9E18 to glycoprotein VI (GPVI). A. Increasing amounts of soluble GPVI-Fc (circles) or GPVI-His (squares) were incubated in 9E18 IgG-coated microtitration wells and detected using horse-radish peroxidase–coupled mouse anti-human Fc specific and anti-6×His. Data are the means of triplicates from 1 representative experiment. B. Purified GPVI-Fc and GPVI-His (1 μg) were immunoblotted with 9E18 or 3J24 (loading control) (2 μg/mL). C. Whole blood was incubated with 4 μg/mL fluorescein isothiocyanate–coupled 3J24 (in blue), 9E18 (in red), or a mouse IgG1 (in black) as isotypic control, and fluorescence was acquired in the platelet gate. Data are from 1 typical experiment out of 20. D. Detection of GPVI in whole platelet lysates (5 or 10 μg proteins) by immunoblotting with 9E18 or 3J24 (2 μg/mL). 3J24 and Ponceau red were the loading controls.
tases. It fully prevented PMA-induced binding of 9E18 to platelets and GPVI-dependent platelet adhesion to immobilized collagen but was without effect on P-selectin exposure (Supplemental Figure III).

In contrast, PMA-induced binding of 9E18 remained unchanged in the presence of 20 μmol/L of the Tyr kinase inhibitor PP1 (28.4 versus 27.7%). FcR was not phosphorylated in conditions leading to GPVI dimerization (PMA- or ADP-activated platelets), indicating that binding of 9E18 to platelets occurs independently of signals downstream of GPVI.

Binding of 9E18 Is a Potential New Marker of Platelet Activation and Efficacy of P2Y12 Antagonists

Because binding of 9E18 is the consequence of an active GPVI modification that favors platelet interaction with fibrillar collagen, it could represent a new circulating biomarker of platelet reactivity in patients. To test this hypothesis, 9E18 binding and P-selectin exposure were measured in PRP from CAD patients (n=45) participating in the BIOCORE-2 study. All patients were under dual antiplatelet therapy, aspirin (75–160 mg/day), and clopidogrel (75 mg/day). A positive correlation was observed between basal 9E18 binding and P-selectin exposure (Spearman r=0.568; P<0.0001) (Figure 5A).

We hypothesized that antagonists of P2Y12 could inhibit ADP-induced 9E18 binding to platelets. To test this hypothesis, 9E18 binding to platelets was measured before and after PRP incubation with ADP in normal subjects and patients treated with clopidogrel (75 mg) (Figure 5B). A highly significant reduction in the response was observed in clopidogrel-treated patients. A good correlation was found between ADP-induced 9E18 binding and vasodilator–stimulated phosphoprotein phosphorylation, which is one of the biological markers of P2Y12 antagonists (Figure 5C).
The 9E18 antibody that was raised against dimeric GPVI was characterized by its extremely poor capacity to bind to monomeric GPVI, whereas it binds to dimeric GPVI with a nanomolar affinity. This observation indicates that the antibody recognizes a specific conformational epitope on dimeric GPVI.

Several groups have reported that GPVI may form a dimer that has functional significance. The X-ray crystallography of soluble GPVI revealed a dimeric conformation. Furthermore, the GPVI-Fc fusion protein has demonstrated effective inhibition of thrombus formation, consistent with its ability to bind fibrillar collagen with high specificity and reasonable affinity. The very large discrepancy between the apparent affinities of monomeric and dimeric GPVI for fibrillar collagen indicate that 9E18 recognizes the conformation of the GPVI dimer favorable for binding to collagen. The capacity of 9E18 to bind to resting platelets was at the limit of the detection in fresh whole blood, indicating that GPVI is mostly monomeric on circulating platelets; the level of 9E18 binding, however, increased with platelet activation and with time as observed for P-selectin exposure, suggesting that dimerization could be activation dependent.

In fact, the observations that 9E18 specifically binds to activated platelets and that binding of 9E18 is exclusively inhibited by soluble GPVI dimers demonstrate that platelet membrane GPVI forms dimers in response to various stimuli.

GPVI has been proposed to be in a monomer-dimer equilibrium at the platelet surface, and ligand binding triggered a very rapid disulfide cross-linking of the GPVI cytoplasmic domains, suggesting that some dimers may exist at the limit of the detection in fresh whole blood, indicating that GPVI is mostly monomeric on circulating platelets; the level of 9E18 binding, however, increased with platelet activation and with time as observed for P-selectin exposure, suggesting that dimerization could be activation dependent.

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platelets suggests that the equilibrium between the monomer and dimeric forms is easily shifted toward the latter.

We indeed observed that stimulating platelets with a weak (ADP) or a strong (TRAP) soluble agonist significantly increased the binding of 9E18, indicating that platelet stimulation brought GPVI monomers together to form dimers. The observation of a double population in ADP- or TRAP-stimulated platelets but not in PMA-treated platelets indicates that regulation of GPVI dimerization depends on the agonist and possibly on the level of intracellular calcium mobilization. In agreement with the increased affinity of GPVI dimers for collagen, the initial interaction of platelets with collagen was favored in relation to the presence of dimers of GPVI at the platelet surface.

In the sequence of events assumed to result in stable platelet adhesion and aggregation, the interaction of GPIb with collagen-bound vWF is thought to precede GPVI binding to collagen. Application of a high shear to PRP triggered platelet aggregation and GPVI dimerization. Furthermore, on washed platelets, shear-induced 9E18 binding and aggregation were dependent on the presence of vWF. We thus showed for the first time that platelet activation by the vWF/GPIb axis has a priming effect on GPVI, resulting in a direct enhancement of GPVI interaction with collagen. The rapid assembly of highly competent dimers of GPVI at sites of vascular lesion represents an important and heretofore unrecognized step in the sequence of events leading to platelet activation by collagen.

The mechanism leading to GPVI dimerization is clearly distinct from the signaling cascade downstream of GPVI: it requires neither FcγR phosphorylation nor the activation of downstream Tyr kinases. Because the assembly of a GPVI dimer is not sufficient to trigger downstream signaling, clusters of at least 2 GPVI-dimers appear to be the minimal signaling unit.22,24 Recent studies have provided evidence that Lyn, an SFK constitutively bound to the Pro-rich motif of the GPVI cytoplasmic domain, is in an activated state25 and that CD148, a Tyr phosphatase, maintains a pool of active SFKs.20 Consistent with the inhibition of collagen-induced platelet activation,29 GPVI dimerization was blocked by PAO, a commonly used inhibitor of Tyr phosphatases.26 Protein disulfide isomerase inhibition by PAO was ruled out by the absence of effect of bacitracin (3 μmol/L) on 9E18 binding (data not shown).

Interestingly, GPVI dimerization is controlled by the intracellular cAMP concentration, as indicated by the inhibition of 9E18 binding to resting as well as to ADP-, TRAP-, or...
that their increased binding to activated platelets could be related to GPVI dimerization. Indeed, the present study, comparing P-selectin exposure and GPVI dimer levels in patients experiencing CAD, demonstrates a good correlation between the 2 markers. GPVI dimerization could be considered an earlier biomarker of platelet activation compared with P-selectin, according to the sequence of events leading to platelet activation. On the other hand, cAMP inhibits GPVI dimerization, whereas antagonists of the ADP receptor P2Y12 prevent the lowering effect of ADP on cAMP. The measure of ADP-induced binding of 9E18 to platelets could thus represent a new marker estimating simultaneously the biological and the functional efficiency of P2Y12 antagonists. This is supported by the observations that ADP-induced GPVI dimerization was blocked (1) in vitro by the P2Y12 antagonist 2MeSAMP and (2) ex vivo, on platelets from patients treated by the thienopyridine clopidogrel. Although numerous platelet function tests have been proposed to identify low responders to P2Y12 antagonists, there is currently no consensus regarding the most appropriate method. GPVI dimerization could be of great interest because it integrates both the initial activation state and the degree of platelet inhibition. Additional studies are now required to determine whether GPVI dimers represent a reliable predictive marker for the risk of arterial thrombosis, or a reliable marker of the reactivity to P2Y12 antagonists, by analyzing 9E18 binding to platelets of age- and sex-matched patients.

In this study, using the monoclonal antibody 9E18 as a specific tracer of dimeric GPVI, we have demonstrated that GPVI is maintained in a monomeric form on resting platelets and that GPVI dimerization is an active process that primes platelet interaction with fibrillar collagen and is controlled by cAMP. Consequently, GPVI dimers could represent a new, sensitive, and early marker of platelet responsiveness.

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**Disclosures**

None.

**References**


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Material and Methods

Reagents: Mouse IgG1 and HRP-coupled goat anti-mouse IgG were from Jackson ImmunoResearch (Suffolk, UK), mouse anti-P selectin from Ancell (Bayport, MN), Alexa-Fluor 568 goat anti-mouse IgG from Invitrogen (Cergy, France), FITC-coupled mouse anti-P-selectin and mouse non-immune IgG1 from Beckman Coulter (Villepintes, France), and rabbit polyclonal anti-FcRγ subunit from Upstate (Lake Placid, NY). Apyrase (grade VII), prostaglandin E1 (PGE1), bovine serum albumin (BSA), Ortho-Phenylenediamine dihydrochloride (OPD), Phorbol 12-myristate 13-acetate (PMA), Phenylarsineoxide (PAO), forskolin and 3-isobutyl-1-methylxanthine (IBMX) were from Sigma (St Louis, MO), S-Nitroso-Nacetyl penicillamine (SNAP) from Calbiochem (San Diego CA), the thrombin-receptor activating peptide (SFLLRN, TRAP-1) from Polypeptides (Strasbourg, France), RGDS peptide from Bachem (Weil am Rhein, Germany), ADP from Stago (Asnières, France) and human vWF from LFB (les Ulis, France).

GPVI-Fc and GPVI-His were produced in HEK cells and affinity purified on Protein A and Ni columns respectively. GPVI-Fc was reduced by 20 mM dithiothreitol and alkylated by 20 mM iodoacetamide. Efficacy of reduction was ~100% as indicated by a single 75-kDa band in SDS-PAGE. Subunits tend to non-covalently reassociate in non-denaturing conditions, as indicated by the presence of two peaks at 70 and 140 kDa in mass spectrometry, the proportion of reassociated dimers being of ~30%.

Binding assays using purified proteins: Microtitration wells were coated with 9E18 IgG (0.2 µg/well) and saturated with BSA (10 mg/mL). Increasing amounts of purified GPVI-Fc or GPVI-His in PBS, containing 1 mg.mL⁻¹ BSA and 0.1% Tween 20, were incubated in coated wells and detected using HRP-coupled anti-human IgG
or anti 6xHis respectively and OPD. Competition experiments were performed on wells coated with GPVI-Fc (0.2 µg/well). 9E18 IgG (0.6 µg/mL) was added to the wells in the presence of increasing amounts of soluble recombinant GPVI-Fc or GPVI-His and detected using HRP-coupled anti-mouse IgG and OPD. Five washes were performed between each step. Data were analyzed and graphs were produced using PRISM GraphPad, (San Diego, CA). Affinity was determined as $K_{D_{app}} = \frac{B_{max} \cdot X}{K_d + X}$ where $B_{max}$ is the maximum specific binding, $K_d$ the equilibrium binding constant and $X$ the ligand concentration.

**Isolation of platelets:** Blood was obtained from healthy volunteers, who had not taken medication for 10 days, after full informed consent according to the Helsinki declaration. Blood was collected in vacutainers containing 0.109 M sodium citrate; platelet-rich plasma (PRP) was obtained by centrifugation at 120 g for 15 min and platelet-poor plasma by centrifugation at 1200 g 12 min. Alternatively, blood was collected on acid-citrate-dextrose anticoagulant (ACD-A) to prepare washed platelets in the presence of apyrase (25 µg.mL$^{-1}$) and prostaglandin E1 (100 nM) as previously reported$^1$. Platelets were resuspended in 5 mM Hepes, 137 mM NaCl, 2 mM KCl, 1 mM MgCl$_2$, 12 mM NaHCO$_3$, 0.3 mM NaH$_2$PO$_4$, 5.5 mM glucose, 2 mM CaCl$_2$, pH 7.4, containing 1mg.mL$^{-1}$ BSA.

**Flow cytometry:** Resting and activated platelets ($5 \times 10^7$.mL$^{-1}$) were incubated with FITC-coupled anti-GPVI or P-selectin antibodies for 20 min and, when needed, fixed with 1% PFA. Samples were analyzed by flow cytometry using an Epics XL (Beckman Coulter Villepinte, France) or an LSRII (BD Biosciences, Le Pont de Claix, France) apparatus. Platelets were gated on forward and side scatter and >95% of events in the gate were positive for CD41. A mouse IgG1 (isotypic control) was used to define negative events in the population of gated platelets. Phosphorylation of
vasodilator–stimulated phosphoprotein (VASP) was measured by quantitative flow cytometry assay (Platelet VASP, Diagnostica Stago, Biocytex, Marseille, France) and using a Coulter EPICS XL cytometer, (Beckman Coulter Inc., Fullerton, California). Blood samples were incubated with prostaglandin E1(PGE1) alone or PGE1+ADP. After cellular permeation, VASP in its phosphorylated state was labelled by indirect immunofluorescence using a specific monoclonal antibody. The P2Y12 reactivity ratio was calculated as [mean fluorescence intensity PGE1-(mean fluorescence intensity PGE1+ADP)/ mean fluorescence intensity PGE1] x 100. Resistance to clopidogrel was defined by P2Y12 reactivity ratio > 50%.

Platelet adhesion: Microtiter plates were coated overnight with type I collagen (20 µg/mL in PBS). After blocking with BSA, platelets (10^8/mL) in Mg^{2+}-free reaction buffer, with or without 300 µM RGDS, were allowed to adhere for 30 min. After gentle washing, adherent platelets were quantified using p-nitrophenyl phosphate as described.

Shear-induced platelet activation: Shear-induced platelet activation was performed as previously described. PRP, containing FITC-coupled 9E18 (4 µg/mL) or isotypic IgG, was submitted to 0 or 4000 s^{-1} during 5 min in a rotative shearing device and immediately analysed by flow cytometry. Alternatively, experiments were performed on washed platelets (3x10^8/mL) supplemented or not with vWF (50 µg/mL)


Supplemental Figures
Figure I: Binding of 9E18 to GPVI monomers and dimers

A: Microtitration wells were coated with GPVI-Fc (2 µg/well). Purified 9E18 IgG (0.6 µg/mL) was incubated in the well in the presence of increasing amounts of soluble GPVI-Fc or GPVI-His or reduced and alkylated GPVI-Fc. Data are from one representative experiment out of 3.

B: 1 µg non-reduced or reduced alkylated GPVI-Fc were immunoblotted with 9E18 or 3J24 (2 µg/mL).

Figure II: Binding of 9E18 to platelets does not require FcγRIIA

PRP was preincubated with the FcγRII-blocking antibody IV.3 (10 µg/mL) before activation by PMA (0.2 µM) for 20 min. Binding of 9E18 to platelets was analyzed by flow cytometry. In grey, resting platelets, in black, PMA-activated platelets, in red,
IV.3 pretreated, PMA-activated platelets. Data are from one representative experiment out of 3.

Figure III: **PMA-induced GPVI dimerization and platelet adhesion to collagen are inhibited by PAO**

A: Washed platelets pretreated or not with PAO (1 µM, 2 min at 37°C) were incubated with PMA (0.2 µM) for 20 min before being analyzed for GPVI expression (FITC-3J24), GPVI dimerization (FITC-9E18) and P-selectin exposure. Results are from 9 independent experiments.

B: Washed platelets (10⁸/mL in reaction buffer without magnesium and containing 300 µM RGDS) were treated with buffer or with PAO, activated by PMA and allowed to adhere on immobilized collagen. Results are from 6 independent experiments.
Material and Methods

Reagents: Mouse IgG1 and HRP-coupled goat anti-mouse IgG were from Jackson ImmunoResearch (Suffolk, UK), mouse anti-P selectin from Ancell (Bayport, MN), Alexa-Fluor 568 goat anti-mouse IgG from Invitrogen (Cergy, France), FITC-coupled mouse anti-P-selectin and mouse non-immune IgG1 from Beckman Coulter (Villepintes, France), and rabbit polyclonal anti-FcRγ subunit from Upstate (Lake Placid, NY). Apyrase (grade VII), prostaglandin E1 (PGE1), bovine serum albumin (BSA), Ortho-Phenylenediamine dihydrochloride (OPD), Phorbol 12-myristate 13-acetate (PMA), Phenylarsineoxide (PAO), forskolin and 3-isobutyl-1-methylxanthine (IBMX) were from Sigma (St Louis, MO), S-Nitroso-Nacetyl penicillamine (SNAP) from Calbiochem (San Diego CA), the thrombin-receptor activating peptide (SFLLRN, TRAP-1) from Polypeptides (Strasbourg, France), RGDS peptide from Bachem (Weil am Rhein, Germany), ADP from Stago (Asnières, France) and human vWF from LFB (les Ulis, France).

GPVI-Fc and GPVI-His were produced in HEK cells and affinity purified on Protein A and Ni columns respectively. GPVI-Fc was reduced by 20 mM dithiothreitol and alkylated by 20 mM iodoacetamide. Efficacy of reduction was ~100% as indicated by a single 75-kDa band in SDS-PAGE. Subunits tend to non-covalently reassociate in non-denaturing conditions, as indicated by the presence of two peaks at 70 and 140 kDa in mass spectrometry, the proportion of reassociated dimers being of ~30%.

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