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FLow-Induced PRotrusions (FLIPRs)

A Platelet-Derived Platform for the Retrieval of Microparticles by Monocytes and Neutrophils

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Rationale: **Platelets are the most important cells in the primary prevention of blood loss after injury. In addition, platelets are at the interface between circulating leukocytes and the (sub)endothelium regulating inflammatory responses.**

Objective: **Our aim was to study the dynamic process that leads to the formation of procoagulant and proinflammatory platelets under physiological flow.**

Methods and Results: **In the present study, we describe the formation of extremely long, negatively charged membrane strands that emerge from platelets adhered under flow. These flow-induced protrusions (FLIPRs) are formed in vitro on different physiological substrates and are also detected in vivo in a mouse carotid injury model. FLIPRs are formed downstream the adherent and activated platelets and reach lengths of 250 μm. FLIPR formation is shear-dependent and requires cyclophilin D, calpain, and Rac1 activation. It is accompanied by a disassembly of the F-actin and microtubule organization. Monocytes and neutrophils roll over FLIPRs in a P-selectin/P-selectin glycoprotein ligand-1–dependent manner, retrieving fragments of FLIPRs as microparticles on their surface. Consequently, monocytes and neutrophils become activated, as demonstrated by increased CD11b expression and L-selectin shedding.**

Conclusions: **The formation of long platelet membrane extensions, such as the ones presented in our flow model, may pave the way to generate an increased membrane surface for interaction with monocytes and neutrophils. Our study provides a mechanistic model for platelet membrane transfer and the generation of monocyte/neutrophil–microparticle complexes. We propose that the formation of FLIPRs in vivo contributes to the well-established proinflammatory function of platelets and platelet-derived microparticles. (*Circ Res*. 2014;114:780-791.)**

Key Words: flow ■ microparticles ■ platelet adhesion ■ proinflammatory platelets ■ shear

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Platelets play a prominent role in the human primary hemostatic response. During thrombus formation, platelets have 2 main functions: (1) initial adhesion to exposed subendothelium, as may occur during injury or rupture of atherosclerotic lesions, and (2) recruitment of circulating platelets in an integrin $\alpha_{IIb}\beta_3$–dependent manner, expanding thrombus volume. The activation of platelets after exposure to strong agonists induces the expression of phosphatidylserine (PS) on the platelet surface, required for the accumulation of clotting factors. Procoagulant platelets form PS-exposing microparticles and further develop into balloon-shaped platelets capable of supporting fibrin formation.[1,2] The formation of procoagulant platelets is triggered by a strong and sustained rise in cytosolic calcium concentration.[3] On depletion of the intracellular calcium stores, store-operated calcium entry (SOCE) is activated, leading to an influx of calcium.[4–6] Additionally, store-independent calcium entry via nonselective cation channels of the transient receptor potential C family can be activated, leading to increased PS exposure and procoagulant activity.[5,6] Mitochondrial events have been implicated as important determinants of platelet procoagulant activity. Calcium transport from the mitochondria is regulated via the formation of the mitochondrial permeability transition pore (MPTP), a nonselective multiprotein pore that spans the inner mitochondrial membrane.[7,8] This process is regulated by the peptidylprolylisomerase cyclophilin D and results in a rapid

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Nonstandard Abbreviations and Acronyms

CRP	collagen-related peptide
FLIPRs	flow-induced protrusions
FACS	fluorescence-activated cell sorting
GPIb	glycoprotein Ib
MPTP	mitochondrial permeability transition pore
PS	phosphatidylserine
PSGL-1	P-selectin glycoprotein ligand-1
OCS	open canalicular system
RICM	reflection interference contrast microscopy
SOCE	store-operated calcium entry

loss of mitochondrial transmembrane potential, causing high levels of PS exposure.[7]

Beside the well-known contribution to thrombus formation, platelets have been implicated in inflammatory diseases, mainly through their capacity to directly interact with leukocytes.[9,10] Activated platelets can bind leukocytes and attract them towards the arterial wall, thereby promoting inflammatory responses, such as atherosclerosis, venous thrombosis, and arthritis.[11–14] Furthermore, activated platelets can bind to both monocytes and neutrophils, forming a circulating complex. Increased numbers of such complexes are reported in patients after percutaneous coronary intervention,[15] acute myocardial infarction,[15] stable coronary artery disease,[16] and ischemic stroke.[17]

The dynamic process that leads to the formation of procoagulant and proinflammatory platelets under physiological flow has never been visualized. In the present study, we show the timed formation of flow-induced protrusions (FLIPRs). These are extremely long, negatively charged membrane strands that emerge from spread platelets after activation. This consequently results in the formation of microparticles and balloon-shaped platelets. FLIPRs are formed via cyclophilin D–dependent calcium transport and require calpain and Rac1 activation. Circulating platelets do not interact with pre-existing FLIPRs, suggesting reduced adhesive properties. Monocytes and neutrophils, however, preferentially roll over FLIPRs and FLIPR-forming platelets in a P-selectin/P-selectin glycoprotein ligand-1 (PSGL-1)-dependent fashion. This interaction leads to the retrieval of FLIPR fragments as microparticles on their surface and leads to their activation.

Methods

Detailed Methods are available in Online Data Supplement.

Blood Collection

Blood was collected from healthy volunteers and anticoagulated with 10% sodium citrate (3.2% wt/vol). Platelet-rich plasma and washed platelets were prepared as described previously.[18]

Real-Time Perfusion Studies

Glass coverslips were placed in a polydimethylsiloxane perfusion chamber coated with fibrinogen (100 μg/mL). Washed platelets were perfused in a calcium-rich buffer at a shear rate of 300 per second and activated by perfusing collagen-related peptide (CRP) (500 ng/mL) over the platelets after 15 minutes of perfusion.

Microparticle Isolation

Washed platelets were perfused in a calcium-rich buffer over fibrinogen and activated with 500 ng/mL CRP. Flowthroughs were collected and centrifuged twice at 1500*g* for 15 minutes in the presence of PGI_2 and 20 mmol/L EDTA. For fluorescence-activated cell sorting (FACS) analysis, the supernatant containing microparticles was incubated with antibodies against glycoprotein Ib (GPIb) and lactadherin. For Western blots, the supernatant was centrifuged at 20 000*g* for 1 hour and the microparticle-containing pellet resuspended in sample buffer in the presence of dithiothreitol. Proteins were separated by SDS-PAGE and stained with anti-GPIb (SZ-2).

Monocyte and Neutrophil Perfusions

Monocytes were isolated using $CD14^+$ magnetic beads from the mononuclear cell fraction obtained via Ficoll separation. Neutrophils were isolated with a 6% Dextran/0.9% NaCl solution followed by a Ficoll. Washed platelets were perfused for 15 minutes followed by activation with CRP for 5 minutes. Monocytes and neutrophils were then perfused, and rolling and adhesion were studied during real-time perfusion. Flowthroughs during these perfusions were captured and stained with CD14 (monocytes), CD66b (neutrophils), GPIb, CD11b, or CD62L.

In Vivo FLIPR Formation

A vascular injury model was used in mice using 7.5% $FeCl_3$. Arteries were fixed 2 minutes after induction of the lesion and processed for SEM analysis.

Results

Formation of Shear-Induced Platelet Membrane Protrusions

Washed platelets were perfused in a calcium-rich buffer (1 mmol/L) through a perfusion chamber coated with fibrinogen or fibronectin at a low arterial shear rate of 300 per second. Platelets adhered readily to the immobilized proteins and became fully spread. CRP (500 ng/mL) was subsequently perfused to further activate the adhered platelets via interaction with glycoprotein VI. On addition of CRP, spread platelets started forming long membrane protrusions (Figure 1A; Online Movie I). These FLIPRs derive from the luminal platelet membrane (Online Movie II) and are formed in the direction of flow (arrowheads in Figure 1A and 1B). The length of FLIPRs was variable; FLIPRs of ≈250 μm were frequently observed. Their initiation and full extension are usually within seconds, but could occasionally take ≈5 minutes. FLIPR formation occurred on 19.5±4.1% of the spread platelets after activation with CRP and was generally detected <5 minutes after CRP addition. A low extent of FLIPR formation was also observed on perfusion of platelet-rich plasma, in the absence of CRP on all physiological substrates, including fibrinogen, fibronectin, collagen peptides GFOGER plus cross-linked CRP, and von Willebrand factor (Figure 1B). However, all these substrates appeared less potent in activating platelets, and hence activation with strong agonists seems to be required to reach a high percentage of FLIPR formation. Platelets with a FLIPR were fully activated, as determined by the expression of P-selectin and decreased cellular content of α-granule marker platelet factor 4 (Figure 1C). The membrane-bound activation marker P-selectin was also present on the FLIPR membrane (Figure 1E and 1F), indicating fusion and membrane delivery from α-granules. To test the possibility that FLIPRs have a procoagulant nature, we analyzed the interaction with annexin A5 to study the potential exposure of negatively charged phospholipids. FLIPRs and accessory platelets readily bound annexin A5 (Figure 1D), whereas platelets without FLIPRs were negative. These results indicate that FLIPR-forming platelets and their membrane extensions have a procoagulant potential.

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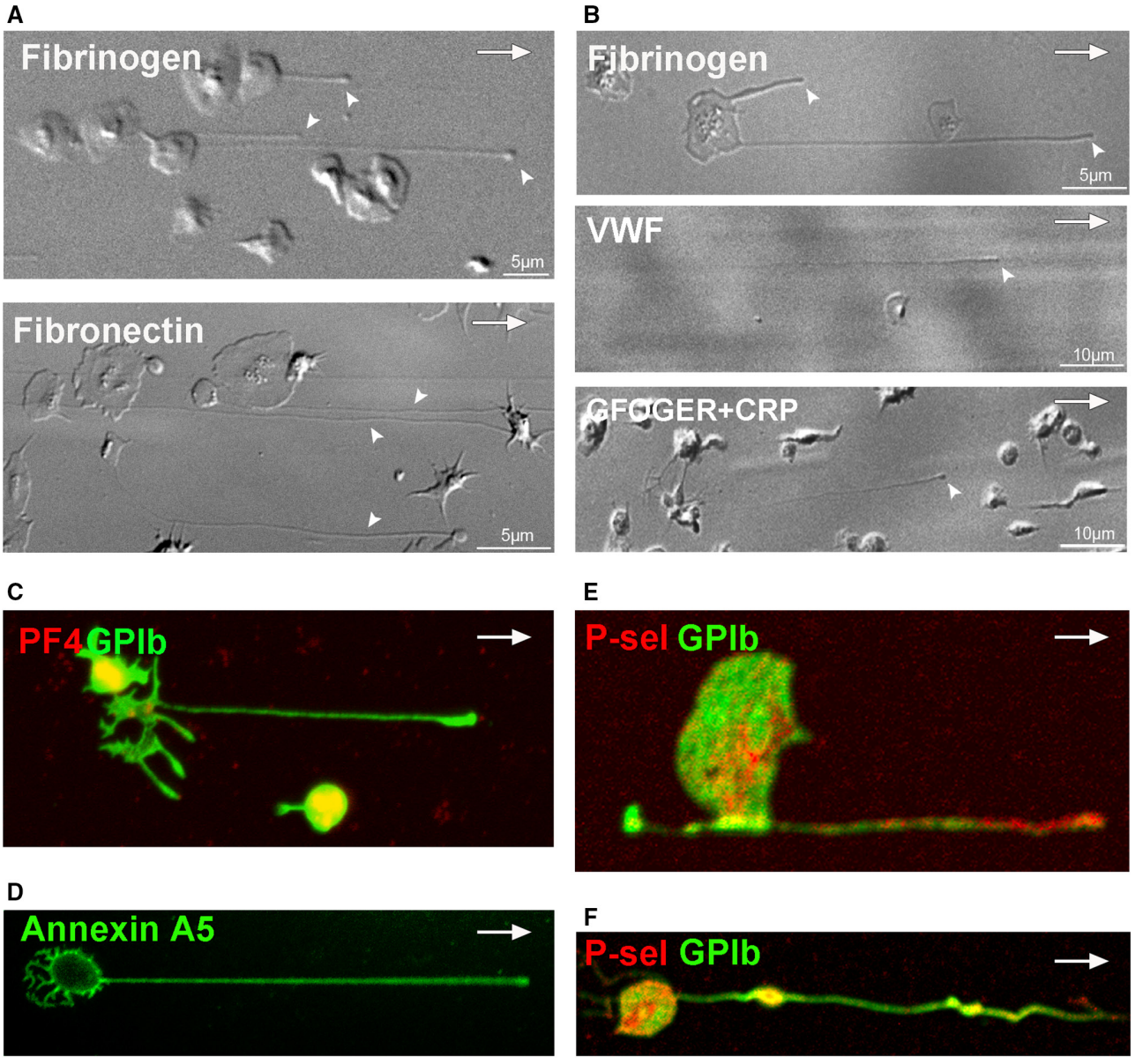

Figure 1. Platelet activation under shear induces a loss of platelet–membrane integrity, resulting in long membrane protrusions. **A**, Washed platelets are perfused over immobilized fibrinogen (**top**) and fibronectin (**bottom**) at a flow rate of 30.3 µL/min, corresponding to a shear rate of 300 per s. Arrowheads indicate flow-induced protrusions formed after addition of 500 ng/mL collagen-related peptide (CRP). **B**, Perfusions over fibrinogen without CRP addition (**top**), von Willebrand factor (VWF) (**middle**), and GFOGER plus crosslinked CRP (**bottom**). **C**, Confocal images showing an overlay of immunofluorescent (IF) staining of platelet factor 4 (red) and glycoprotein Ib (GPIb; green). **D**, Fluorescent staining for annexin A5. **E** and **F**, Confocal images showing IF staining of P-selectin (red) and GPIb (green). Flow direction is indicated with an arrow.

FLIPR Formation Requires Membranes of the Open Canalicular System and Disruption of the Cytoskeleton

FLIPR elongation was accompanied by major changes in platelet morphology. These included a change in shape and size (Figure 2A–2C; Online Movie III) of the adherent platelet, frequently with an almost complete loss of platelet membrane integrity and a disassembly of the underlying cytoskeleton (arrowheads in Figure 2C). The formation of long membrane protrusions requires a high amount of platelet membrane, presumably generated by the membrane reservoir of the open canalicular system (OCS). Because these internal stores harbor GPIb, we determined the mean GPIb fluorescent intensity in protruding and nonprotruding cells spread on fibrinogen, as a measurement for OCS membrane consumption through FLIPR formation. The mean GPIb fluorescent intensity appeared >50% decreased in platelets that form FLIPRs as compared with platelets without a FLIPR (Figure 2E), indicating significant membrane loss from adherent platelets at the expense of forming protrusions. Fluorescent staining of the actin cytoskeleton using phalloidin-FITC revealed a characteristic filamentous staining pattern in intact spread platelets (Figure 2D, left panel). In contrast, FLIPR-forming platelets showed substantial disorganized actin architecture (Figure 2D, top right panel). Actin patches were frequently decorating the FLIPR membrane in a bead-like fashion (arrowheads in

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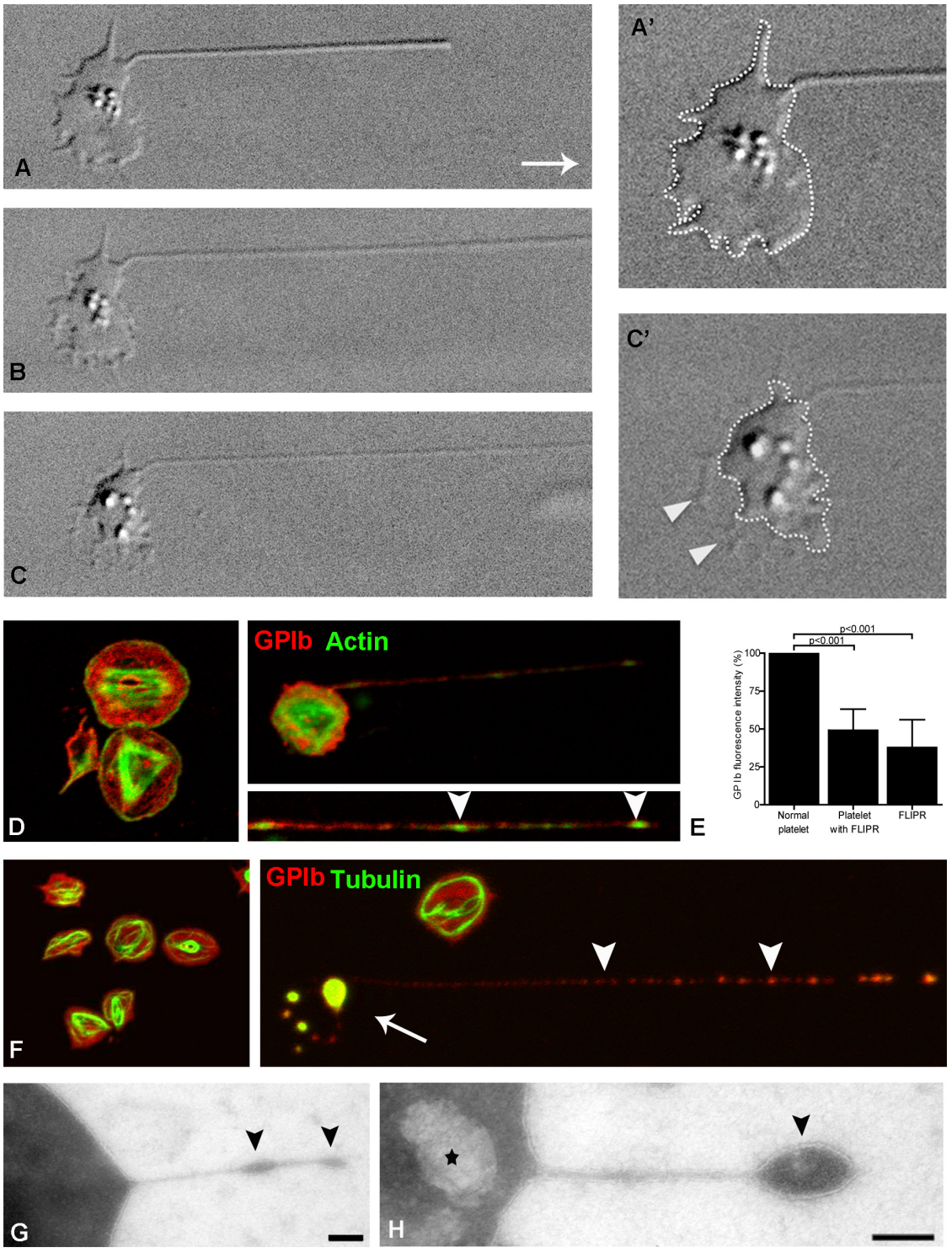

Figure 2. Loss of platelet integrity and cytoskeletal disassembly during flow-induced protrusion (FLIPR) formation. A to **C**, Still images from a videorecording of FLIPR formation in the direction of the flow, induced by collagen-related peptide (CRP). IIa indicates thrombin; and WP, washed platelet. Substrate is fibrinogen; shear rate is 300 per s. Flow direction is indicated with an arrow. The adherent platelet cell body decreases in size (highlighted by the dashed area in **A**′ and **C**′), leaving membrane and cytoskeletal remnants as footprints. **D**, Confocal images of normal (**left**) and FLIPR-forming platelets (**right**). Platelets were immunostained with anti-GPIb and actin as indicated. Disassembly of actin in cell body and presence of actin nodules in FLIPRs (arrowheads in **D**). **E**, Quantification of the mean fluorescent intensity of normal and FLIPR-forming platelets. Twenty platelets from 5 different donors were measured. Error bars indicate standard deviation. **F**, Immunostaining of α-tubulin (glycoprotein Ib [GPIb], red; α-tubulin, green; **bottom**). Note the disorganized staining of FLIPR-forming platelet. Normal platelets indicated on the **left**, platelets with FLIPR on the **right**. Arrowheads indicate disrupted cytoskeleton. **G** and **H**, Whole mount TEM images of platelets and FLIPRs on electron microscopy formvar grids. Arrowheads indicate thickened membrane blebs on the FLIPR. Star represents platelet open canalicular system. Scale bars, 200 nm.

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Figure 2D, bottom right panel). In non–FLIPR-forming spread platelets, microtubules were arranged in a characteristic circular fashion (Figure 2F, left panel) and became disorganized in platelets forming protrusions (arrow in Figure 2F, right panel). Whole mount TEM analysis revealed thin elongated membrane protrusions extending downstream of the spread platelets (Figures 2G and 2H). These membranes expose frequently thicker regions particularly at their downstream ends that contain electron-dense material, presumably actin (arrowheads in Figure 2G and 2H). These results indicate that platelet FLIPR formation requires both OCS consumption and loss of F-actin and microtubule integrity. The final end-stage morphology of the adhered platelet often resembled that of balloon-shaped ghosts (arrow in Figure 2F, right panel).

Store-Operated and Store-Independent Calcium Entry Are Involved in FLIPR Formation

Flow experiments over fibrinogen-coated surfaces using citrated platelet-rich plasma resulted in low FLIPR formation (3.1±0.3%). EGTA completely blocked the formation of FLIPRs (Figure 3A). Also, washed platelets perfused over fibrinogen did not form FLIPRs in the absence of extracellular calcium. The addition of CRP resulted in extensive FLIPR formation on fibrinogen in the presence of calcium (19.5±4.1% of platelets; Figure 3C). No FLIPR formation was observed when CRP was added to a calcium-free buffer. The influx of calcium was visualized using Oregon green labeling. CRP stimulation of spread platelets in the presence of calcium revealed a distinct calcium peak before the formation of FLIPRs (arrow in Figure 3B), indicating an influx of calcium into the cytoplasm (Figure 3C). The addition of thrombin (IIa; 0.5 U/mL) resulted in 17.5±5.6% of FLIPR formation, whereas the simultaneous addition of CRP and thrombin resulted in high (79.4±5.6%) FLIPR formation <2 minutes (Figure 3C). After 5 minutes of stimulation, these FLIPRs frequently severed, leaving behind typical balloon-shaped platelet remnants (Figure 3C).

We next investigated the role of SOCE and store-independent calcium entry on FLIPR formation. First, 2-aminoethoxydiphenylborate was added to block SOCE.[19] The addition of 2-aminoethoxydiphenylborate after the spreading of platelets effectively prevents FLIPR formation on addition of CRP (2.0±1.1% of platelets; Figure 3D). Furthermore, the induction of direct calcium influx from intracellular stores using thapsigargin[4,20] completely restored the low abundant FLIPR formation on fibrinogen-adherent platelets to 80.9±5.6% (Figure 3D). Previous studies have indicated that dual stimulation with both CRP and thrombin results in store-independent calcium entry, involving sodium entry via transient receptor potential C channels,[5,6] leading to increased PS exposure. Store-independent calcium entry was inhibited by the addition of SKF96365 together with CRP and thrombin and resulted in decreased FLIPR formation (1.9±0.5% of platelets; Figure 3E). The stimulation of store-independent calcium influx was achieved by the addition of 1-oleoyl-2-acetyl-sn-glycerol, resulting in an increase in FLIPR formation (49.5±5.8% of platelets; Figure 3E). This suggests that beside SOCE, store-independent calcium entry is also involved in the formation of FLIPRs.

Platelet FLIPR Formation Depends on Cyclophilin D–Dependent Calcium Transport, and Rac1 and Calpain Activation

The MPTP seems an important checkpoint for shedding of platelet-derived microparticles and was, furthermore, shown to be an important regulator in platelet PS exposure. We, therefore, investigated the role of cyclophilin D, which regulates calcium transport from the mitochondria via the formation of MPTP.[7,8] The inhibition of cyclophilin D by cyclosporin A resulted in a significant decrease in FLIPR formation on addition of CRP (1.7±0.8% of platelets; Figure 3F). Cyclosporin A not only inhibits cyclophilin D but also inhibits cyclophilin A and calcineurin. Therefore, we have used direct inhibitors of cyclophilin A and calcineurin (FK506). The inhibition of cyclophilin A or calcineurin did not have any effect on FLIPR formation (Figure 3F). Furthermore, direct inhibition of MPTP opening using bongkrekic acid resulted in the inhibition of FLIPR formation similar to cyclosporin A (2.4±1.3% of platelets; Figure 3F). Although we could not block cyclophilin D specifically, our data indicate that FLIPR formation is a cyclophilin D–dependent process.

Recent studies have demonstrated that the calcium-dependent protease calpain is responsible for the formation of procoagulant platelets, which is accompanied by a closure of integrin $\alpha_{IIb}\beta_3$ and subsequent cleavage of cytoskeletal proteins.[8,21] Our next approach was to study the role of calpain in FLIPR formation by the inhibition of calpain with both calpeptin (100 μg/mL) and MDL28170 (200 μmol/L). The inhibition of calpain completely blocked FLIPR formation, indicating that calcium-dependent calpain activation is essential for the formation of FLIPRs (Figure 3G).

Small GTPases play an essential role in the regulation of cell adhesion, motility, proliferation, and differentiation. RhoA, Rac1, and CDC42 are the most characterized GTPases and known for their role in assembling and organizing the actin cytoskeleton.[22,23] We have inhibited these 3 small GTPases by the addition of specific inhibitors (GSK 429286, NSC 23766, and ZCL 278, respectively). The inhibitors were added after platelet spreading together with the agonists CRP, thrombin, or a mixture of CRP and thrombin. Only Rac1 inhibition resulted in impaired FLIPR formation (Figure 3H). This small GTPase was previously shown to be essential for platelet lamellipodia formation.[24]

FLIPR Severing and Formation of Microparticles

Reflection interference contrast microscopy (RICM) was used to study the interaction of FLIPRs with the various substrates during perfusion. Spread platelets showed distinct focal membrane attachment sites to their different substrates, as visualized by the multiple dark contact areas revealed in RICM mode. FLIPRs themselves revealed little interaction sites with the substrate (Figure 4A, differential interference contrast microscopy; Figure 4B, RICM), with the exception of downstream tips. These observations support the thought that the membranes probably derive from the luminal aspect of adherent cells. Interestingly, adherent platelets that formed FLIPRs showed reduced adhesive contact sites, indicating the removal of membrane from the substrate. During perfusion, many FLIPRs severed from the platelets and further disintegrated into smaller fragments, presumably becoming microparticles.

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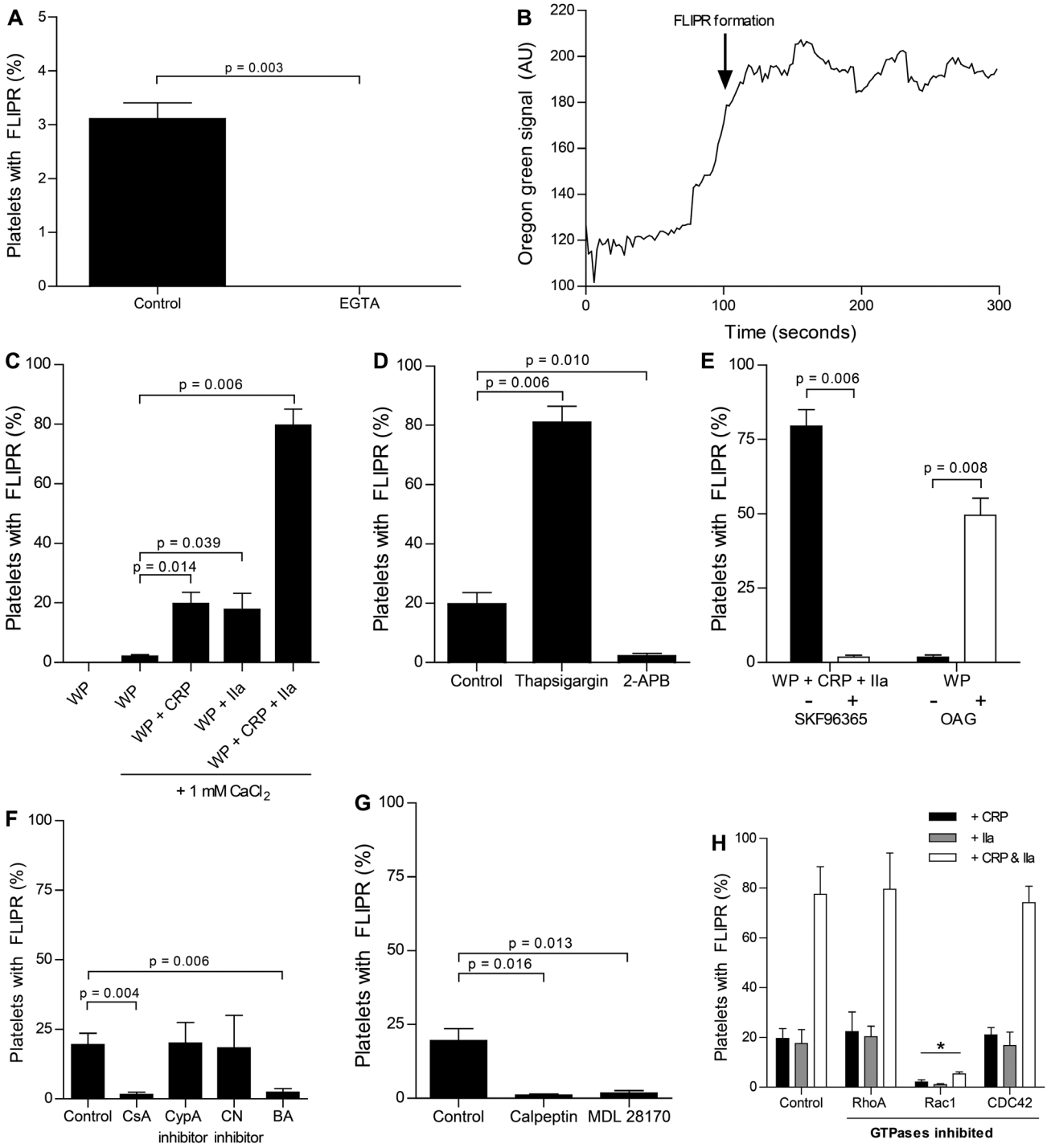

Figure 3. Cyclophilin D–dependent Ca^{2+} signaling and activation of Rac1 and calpain lead to flow-induced protrusion (FLIPR) formation. A, Perfusion of citrated platelet-rich plasma in the absence and presence of calcium chelator EGTA (5 mmol/L). **B**, Calcium flux indicated by an increase in Oregon green signal during perfusion over fibrinogen after collagen-related peptide (CRP) activation. Arrow indicates the moment of FLIPR formation. **C**, Perfusion of washed platelets over fibrinogen in the presence and absence of calcium (1 mmol/L), CRP (500 ng/mL), or thrombin (IIa; 0.5 U/mL). **D**, Perfusion over fibrinogen followed by the addition of CRP with or without thapsigargin (1 μmol/L) or 2-aminoethoxydiphenylborate (2-APB; 50 μmol/L). **E**, Perfusion over fibrinogen followed by the addition of CRP and thrombin in the presence and absence of SKF96365 (100 μmol/L), and washed platelets alone in the presence and absence of 1-oleoyl-2-acetyl-sn-glycerol (OAG; 50 μg/mL). **F**, Washed platelets were perfused over fibrinogen followed by the addition of CRP with or without cyclosporin A (CsA; 4 μmol/L), cyclophilin A inhibitor (CypA inhibitor; 1μg/mL), calcineurin inhibitor (CN inhibitor; 50 μmol/L), and bongkrekic acid (BA; 50 μmol/L). **G**, Calpeptin (100 μg/mL) and MDL 28170 (200 μmol/L) were added with CRP to washed platelets perfused over fibrinogen. Results of 3 independent flow experiments were quantified. Error bars indicate standard deviation. **H**, Perfusion over fibrinogen followed by the addition of CRP with or without GSK 429286 (RhoA inhibitor; 1 μmol/L), NSC 23766 (Rac1 inhibitor; 300 μmol/L), and ZCL 278 (CDC42 inhibitor; 50 μmol/L).

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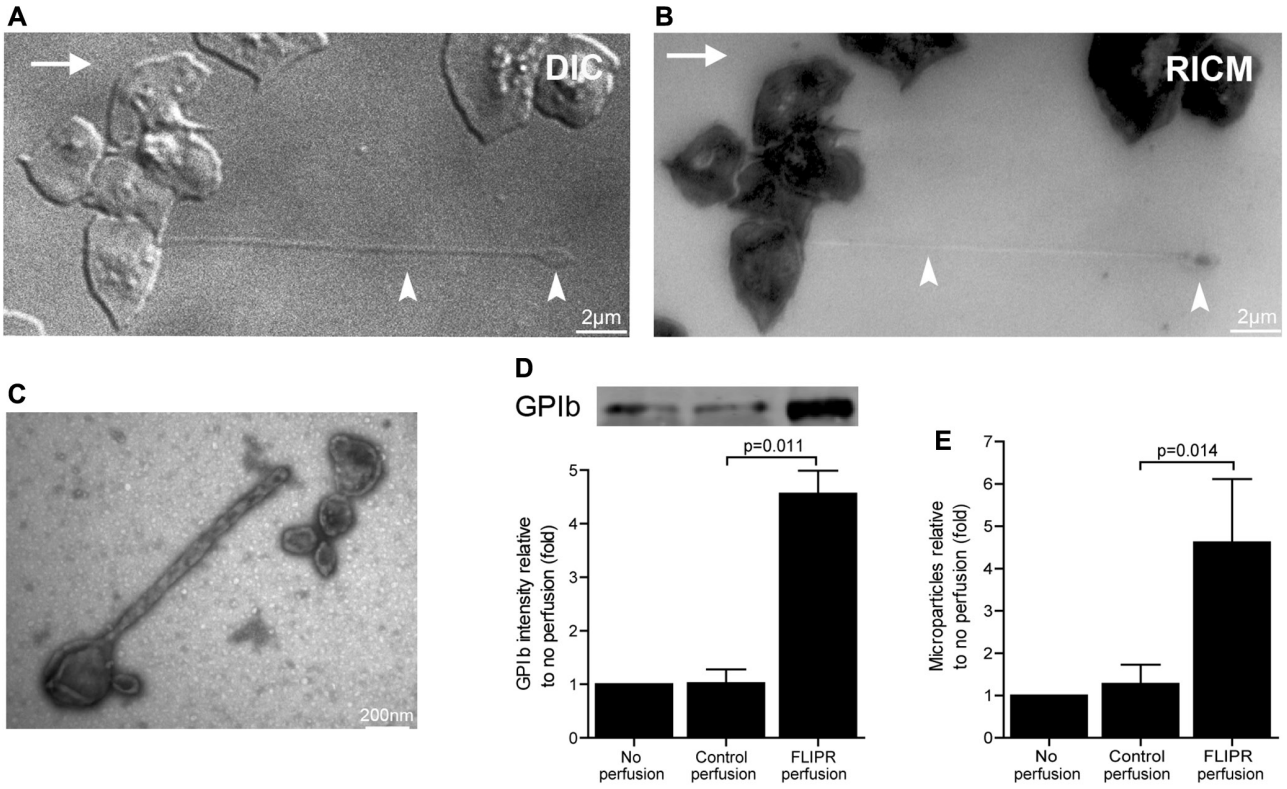

Figure 4. Flow-induced protrusion (FLIPR) formation leads to the formation of platelet microparticles. A and **B**, Differential interference contrast microscopy (DIC) recording (**A**) and corresponding reflection interference contrast microscopy (RICM) picture (**B**) showing surface contact in black and no surface contact in white. Arrowheads indicate transient interaction of FLIPRs with the substrate. Flow direction is indicated with an arrow. **C**, Whole mount TEM images of the flowthrough captured after perfusion. Elongated membrane fragments ≥1.5 μm long and ≈100 nm thick. **D**, Western blot analysis of glycoprotein Ib (GPIb) on microparticle fractions isolated from the flowthrough. Data are depicted as mean GPIb intensity relative to the fractions obtained from control without perfusion. **E**, Fluorescence-activated cell sorting analysis on microparticle-rich flowthrough. The number of GPIb$^+$/lactadherin$^+$ particles was quantified. Data are expressed as fold increase in the amount of microparticles compared with control without perfusion. Averages are shown of 3 independent flow experiments. Error bars indicate standard deviation.

This severing usually occurred within seconds, but could also take several minutes and was shear-dependent.

We next captured the microparticles that were released during perfusion at the outlet of the flow chamber, the flowthrough, for further analysis. Flowthroughs derived from experiments where high numbers of FLIPRs were formed (ie, after addition of CRP) were compared with control perfusions in the absence of CRP and with nonperfused, nonactivated platelets. Membrane fractions from the flowthrough were isolated by differential centrifugation, absorbed to electron microscopy grids, and visualized by TEM. They consisted of elongated membrane structures of variable length and measured generally 30 to 70 nm in diameter (Figure 4C). They frequently exhibited a larger membrane domain at 1 end ≈300 nm in diameter. These extended membrane microparticles were only found in flowthroughs under conditions where FLIPRs were formed and were absent in the flowthroughs of control perfusions. To further characterize these microparticles, we collected the flowthrough after perfusion with or without added CRP and performed a Western blot using anti-GPIb antibodies. As expected, GPIb intensity was significantly increased in the samples with added CRP, consistent with FLIPR severing and microparticle formation (4.6±0.4-fold increase in GPIb intensity; Figure 4D). Subsequent FACS analysis confirmed the presence of negatively charged phospholipids (lactadherin$^+$) and revealed that GPIb$^+$/lactadherin$^+$ particles were increased in number after FLIPR formation as compared with control samples (control perfusion, 1.3±0.4; FLIPR perfusion, 4.6±1.4-fold increase in microparticles; Figure 4E).

These results indicate that the conditions that promote FLIPR generation are directly coupled to the formation of procoagulant microparticles. In an attempt to visualize real-time local fibrin formation on platelet-forming FLIPRs, we performed perfusions with recalcified plasma. Fibrin formation was observed throughout the whole perfusion chamber and did not allow us to conclude whether fibrin generation was selectively initiated on the procoagulant FLIPRs (data not shown).

FLIPRs Attract, Capture, and Activate Circulating Monocytes and Neutrophils

To study the possible role of FLIPRs in recruiting other circulating cells, we perfused isolated monocytes and neutrophils in a calcium-rich buffer (1 mmol/L $CaCl_2$) over FLIPR-forming platelets. Both cell types rolled over FLIPR-forming platelets, thereby decreasing their velocities (Figure 5A; Online Movie IV). The addition of an anti–P-selectin antibody completely blocked both monocyte and neutrophil rolling on FLIPRs, indicating that this interaction is P-selectin/PSGL-1–dependent (Figure 5B; Online Movie V). Interestingly, the temporal interactions with FLIPRs frequently resulted in severing of the

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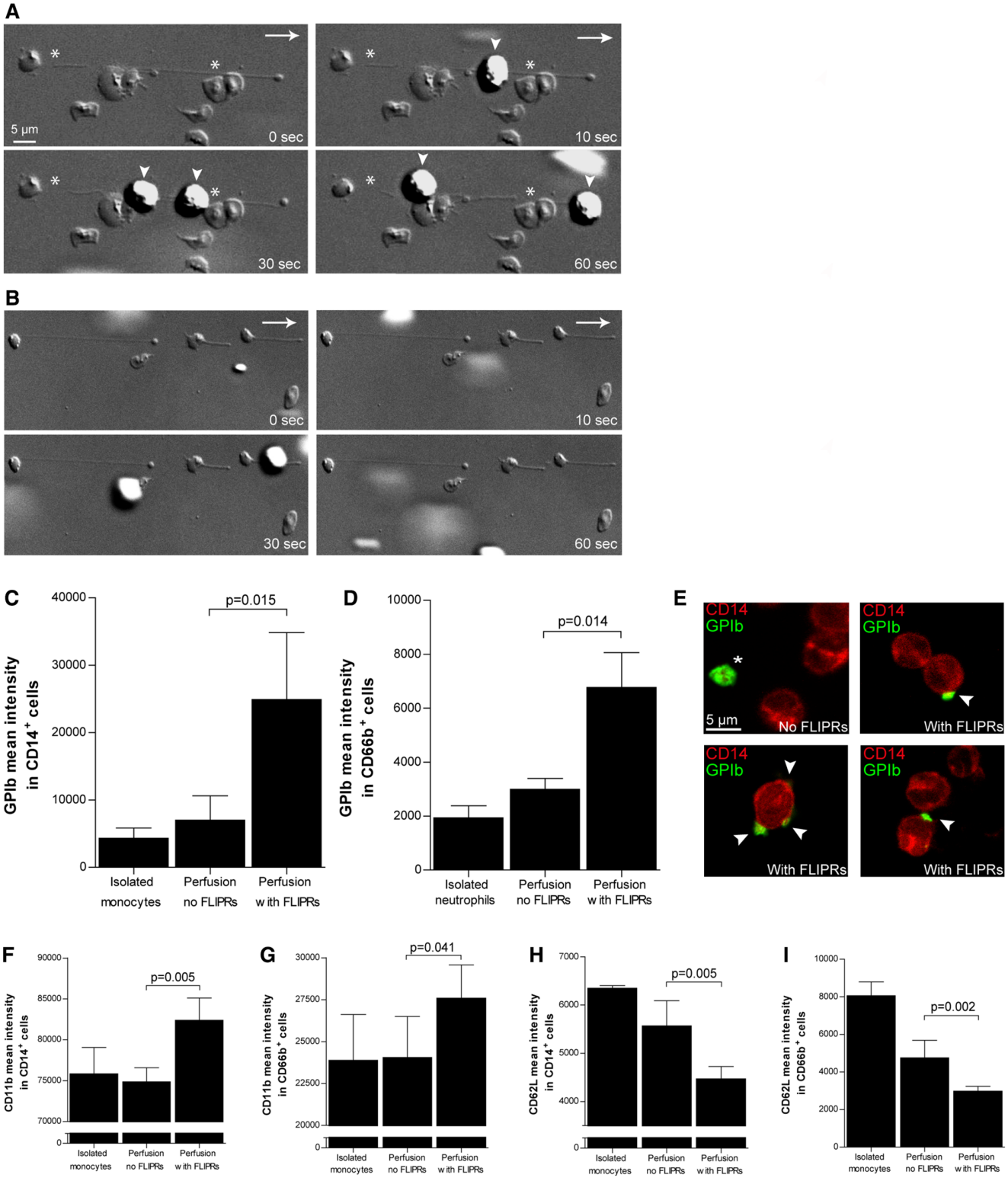

Figure 5. Flow-induced protrusions (FLIPRs) capture monocytes and neutrophils from the circulation, leading to the activation and complex formation with platelet microparticles. A, Monocytes and neutrophils were perfused over FLIPRs to study rolling. Monocyte perfusion is depicted in these images; rolling cells are indicated with an arrowhead. **B**, Anti–P-selectin addition resulted in complete inhibition of monocyte and neutrophil rolling. Flow direction is indicated with an arrow. **C** and **D**, Monocytes (**C**) and neutrophils (**D**) were captured in the flowthrough and the glycoprotein Ib (GPIb) intensity on $CD14^+$ and $CD66b^+$ cells was measured using fluorescence-activated cell sorting analysis. **E**, Captured monocytes from the flowthrough were stained for CD14 and GPIb. Intact platelet is indicated with an asterisk. The size of adhered $GPIb^+$ particles indicates the adhesion of platelet microparticles. Captured monocytes and neutrophils in the flowthrough were analyzed for activation markers CD11b (**F**, monocytes; **G**, neutrophils) and L-selectin shedding (by a decrease in CD62L intensity; **H**, monocytes; **I**, neutrophils). Results of 3 independent experiments were quantified. Error bars indicate standard deviation.

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FLIPR membranes, suggesting transfer of FLIPR fragments (microparticles) to the tethering cells (Figure 5A, asterisk; Online Movie IV). To confirm that FLIPR membranes are delivered to the circulating monocytes and neutrophils, we next analyzed the presence of GPIb$^+$ particles on CD14$^+$ (monocytes) and CD66b$^+$ (neutrophils) cells. Monocytes and neutrophils that were perfused over FLIPR-forming platelets were captured and incubated with antibodies against CD14 or CD66b, and GPIb. GPIb intensity in CD14$^+$ and CD66b$^+$ cells was measured by FACS and was found significantly higher in monocytes and neutrophils that were perfused over FLIPRs as compared with controls without FLIPRs (Figure 5C and 5D). Confocal microscopy analysis confirmed that both monocytes and neutrophils contained bound GPIb-positive platelet patches (arrowheads in Figure 5E). These patches were generally smaller than intact platelets (asterisk in Figure 5E), indicating that they represent platelet fragments presumably originating from fragmentation during transient interactions with FLIPRs under flow.

We next measured whether monocytes and neutrophils perfused over FLIPRs become activated. An increase in CD11b expression and an increase in L-selectin shedding (as measured by a decreased CD62L intensity) are common characteristics of activated monocytes and neutrophils. Both cell types show an increased expression of CD11b after interaction with FLIPR-forming platelets, as compared with perfusion in the absence of FLIPRs (Figure 5F and 5G). Also L-selectin shedding was increased when monocytes and neutrophils were perfused in the presence of FLIPRs as compared with perfusion in the absence of FLIPRs (Figure 5H and 5I). These results show that platelet FLIPR formation contributes to the capturing of circulating monocytes and neutrophils and simultaneous delivery of platelet membranes to the surface of these circulating cells, thereby supporting complex formation and their subsequent activation.

In Vivo FLIPR Formation After Carotid Injury

We next assessed whether such long membrane extensions are also formed in vivo. To this end, we used a mouse carotid injury model. Carotid arteries were treated with $FeCl_3$ to induce a vascular lesion. After 2 minutes of blood flow, samples were fixed and analyzed by SEM. We found multiple elongated membrane structures that originated from the adherent platelets, and essentially as described in our in vitro model, these elongated membrane extensions are oriented downstream the adherent platelets in the direction of flow (arrowheads in Figure 6A and 6B). These data show that FLIPR formation occurs also in vivo.

Discussion

In the present study, we describe the formation of platelet membrane extensions, termed FLIPRs, which develop downstream from adherent spread platelets after activation of cyclophilin D, calpain, and the small GTPase Rac1. FLIPRs derive from the luminal site of adherent platelets and can reach lengths of ≈250 μm, thereby consuming the intracellular OCS membrane stores leading to platelet disintegration and formation of typical balloon-shaped platelets.[1,2] FLIPRs severe as a result of forces generated by shear stress and transient interactions with other cells, including monocytes and neutrophils, which selectively roll over FLIPRs in a P-selectin/PSGL-1–dependent fashion. These transient interactions of monocytes and neutrophils with FLIPRs resulted in the retrieval of membrane fragments from FLIPRs, thereby forming microparticle–monocyte and microparticle–neutrophil complexes, leading to the subsequent activation of monocytes and neutrophils (Figure 7). We propose that platelet protrusions may serve as a surface platform to capture circulating inflammatory cells. These interactions promote the selective transfer of platelet membranes to the monocytes and neutrophils that consequently become activated, leading to the progression of inflammatory processes.

Platelets store membrane in the OCS. This membrane reservoir is crucial for the platelet's capacity to spread, but is probably equally important to form long membrane extensions.[25] The loss of mean GPIb fluorescent intensity on FLIPR-forming platelets indicates that OCS stores are depleted, thereby supplying membrane for FLIPRs. Previous studies have shown the formation of membrane extensions on platelets interacting at high shear rates to von Willebrand factor.[26,27] Although these membrane extensions, termed tethers, show similarities with the present FLIPRs, they differ in several aspects. Tethers are exclusively generated

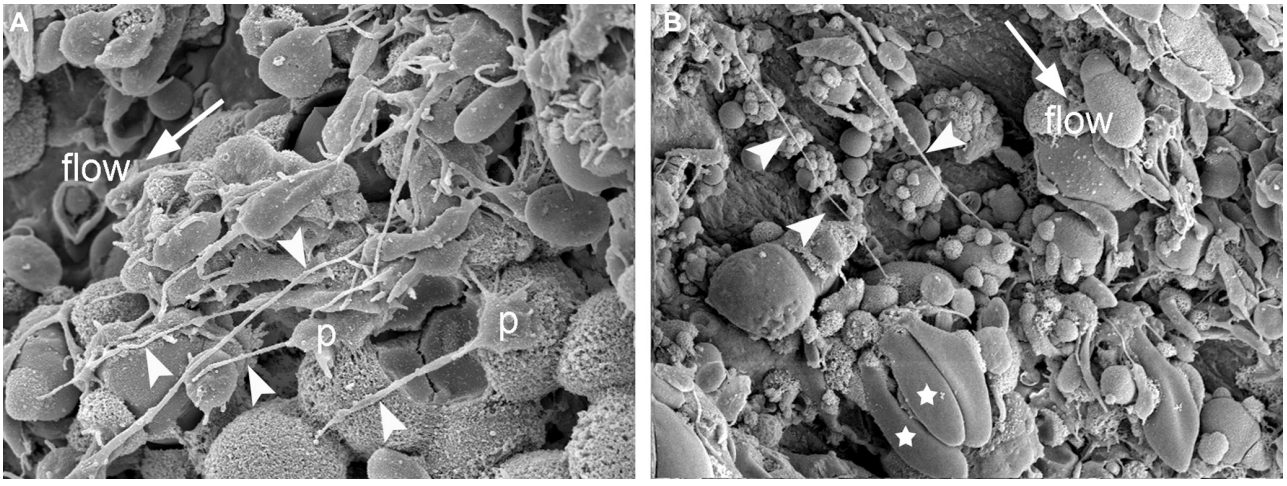

Figure 6. Flow-induced protrusion formation in an in vivo mouse artery injury model. A and **B**, SEM images of $FeCl_3$-injured carotid artery 2 min after application of the injury. Long membrane protrusions (arrowheads) originating from adherent platelets (p) are formed in the direction of flow. Drop-shaped red cell morphology (star in **B**) is indicative of flow direction. Magnification, ×6500 (**A**) and ×3500 (**B**).

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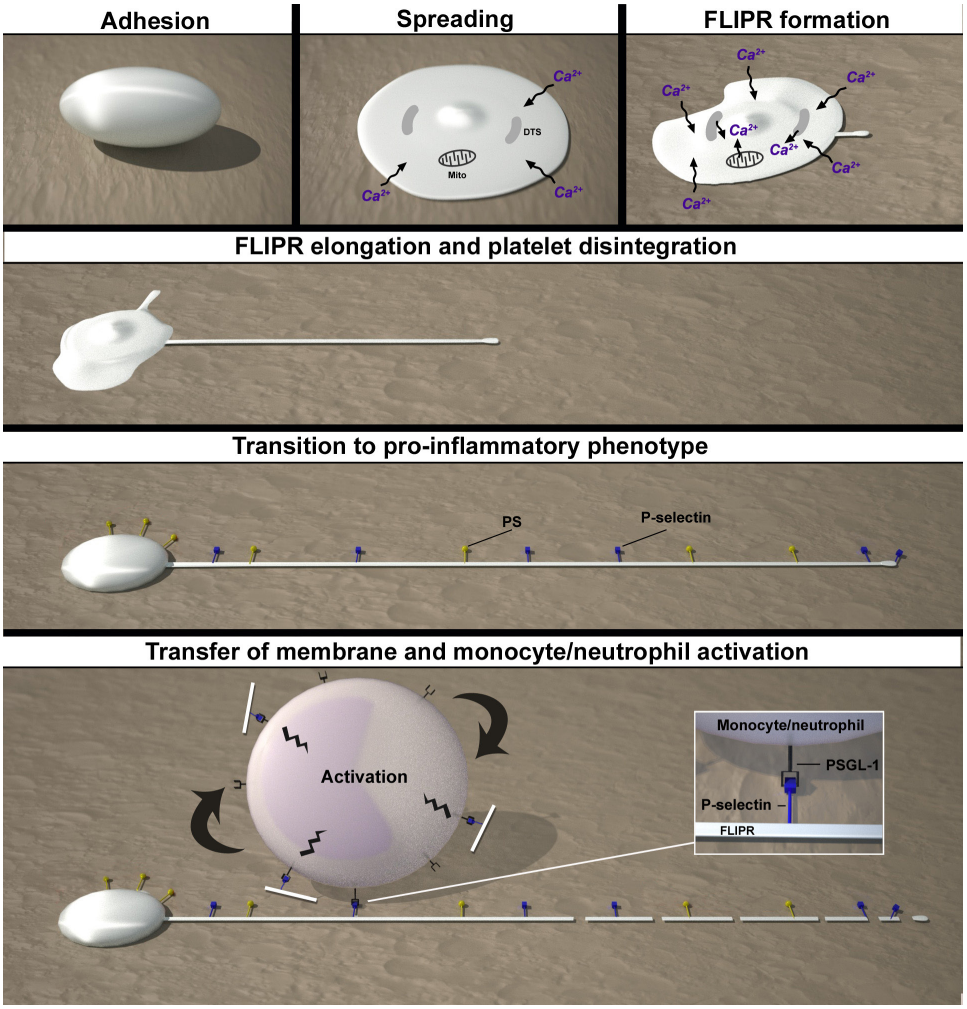

Figure 7. Model of flow-induced protrusion (FLIPR) formation and membrane transfer. Platelet adhesion and spreading on a physiological surface. Extracellular calcium entry and depletion of intracellular stores raise the cytosolic calcium concentration. DTS indicates dense tubular system; and mito, mitochondria. High cytosolic calcium and shear forces induce the formation and elongation of long membrane protrusions (FLIPRs). Phosphatidylserine (PS) and P-selectin are expressed on the platelet and FLIPR membrane. Monocytes and neutrophils roll over FLIPRs, retrieve membrane fragments, and become activated.

on von Willebrand factor at high shear rates and do not depend on platelet activation. Furthermore, tethers form upstream of platelets, and they serve to decelerate fast-moving platelets through the formation of transient adhesion points.

The formation of procoagulant balloon-shaped platelets has been described in vitro, using a combination of collagen and thrombin or alternatively through the addition of a calcium ionophore.[1,2,28] Such platelet activation with strong agonists results in a sustained rise in cytosolic calcium and PS exposure, thereby supporting thrombin and fibrin generation and the formation of microparticles.[1,3,28] These procoagulant platelets are referred to as balloon-shaped platelets, collagen- and thrombin-activated platelets, and sustained calcium-induced platelets, all describing a similar phenotype.[1,9,29] In our present flow model, we observed essentially the same phenotype. FLIPRs are induced by a combination of physiological shear stress and cellular activation. On platelet activation, intracellular calcium stores are depleted. Both store-operated and store-independent calcium entry are activated and result in a sustained rise in cytosolic calcium. MPTPs, which regulate calcium transport from the mitochondria, are formed under the control of cyclophilin D. Calpain is activated and responsible for the cleavage of cytoskeletal proteins. These processes together are required for FLIPR formation and high expression of PS. A limitation of our study is the lack of specific cyclophilin D inhibitors. We are, therefore, not able to firmly establish the role of cyclophilins in FLIPR formation. However, with no effect on FLIPR formation on blocking of cyclophilin A or calcineurin, we think that FLIPR formation is cyclophilin D–dependent. FLIPRs bind annexin A5, and thus their formation results in an extension of the procoagulant platelet surface. Importantly, this increased platelet surface does not bind other platelets, confirming what has been described previously for sustained calcium-induced platelets, as a result of the calcium-dependent downregulation of the adhesive function of integrin $\alpha_{IIb}\beta_3$.[10] Balloon-shaped platelet remnants exhibit high PS exposure on their outer membrane leaflet and support the formation of thrombin and fibrin.[1,28–30] Although the procoagulant properties of balloon-shaped platelets are well described,[28] we found no evidence that the formation of fibrin was specifically initiated by FLIPRs.

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The adhesion of monocytes and neutrophils to activated endothelial cells and platelets is a key step in the inflammatory response. Our real-time flow experiments show that both circulating monocytes and neutrophils selectively roll over the long membrane extensions in a P-selectin/PSGL-1–dependent manner. In a similar fashion, neutrophil-derived membrane tethers have been shown to recruit other neutrophils, possibly through a mechanism that depends on L-selectin/PSGL-1 interaction.[31] The capacity of platelets to regulate inflammatory responses is becoming firmly established. Sustained calcium-induced platelets have a proinflammatory phenotype and support the capturing and spreading of neutrophils.[9] We show here that rolling of monocytes and neutrophils over FLIPRs results in transient tethering interactions and FLIPR fragmentation. Both monocytes and neutrophils were capable of capturing membrane fragments from the FLIPRs. Thus, monocyte– and neutrophil–FLIPR interactions support these cells to capture platelet microparticles on their surface under flow conditions. Previous studies have shown that incubation of monocytes with procoagulant microparticles results in monocyte activation, thereby promoting their migration and differentiation.[32] Additionally, monocyte adhesion to platelets resulted in the release of cytokines, thereby further promoting an inflammatory phenotype.[33] Our present data, showing increased CD11b expression and L-selectin shedding on both monocytes and neutrophils after rolling over the FLIPRs, are in accordance with these studies. Furthermore, other studies have shown that platelets are able to induce a proinflammatory phenotype on monocytes and neutrophils on complex formation, resulting in increased adhesive properties toward endothelial cells.[34,35] This in turn is known to increase the progression of inflammatory diseases such as arthritis and atherosclerosis.[11,14,36–38] Monocytes and neutrophils circulating in complex with platelets are profound markers for cardiovascular disease. Increased complexes have been measured after percutaneous coronary intervention,[15] acute myocardial infarction,[15] stable coronary artery disease,[16] graft occlusion,[39] and ischemic stroke.[17] We suspect that complex formation with platelet microparticles is an underestimated phenomenon, which cannot be distinguished from complex formation with intact platelets by FACS analysis. It is, therefore, plausible that previous studies that claimed to measure platelet monocyte and neutrophil complexes did, in fact, measure complex formation with platelet microparticles.

In an attempt to visualize the formation of these membrane extensions in vivo, we have used a mouse $FeCl_3$ injury model to induce a vascular lesion and visualized FLIPRs using SEM analysis. We demonstrated membrane extensions with the same characteristics as FLIPRs shown in vitro. The membrane extensions find their origin on adherent platelets and are oriented in the flow direction, defining them as FLIPRs. Whether FLIPR formation in vivo plays a role in the proinflammatory function of platelets remains to be shown.

In conclusion, we have described the formation of long membrane extensions that derive from adherent and activated platelets both in vitro and in vivo. FLIPRs are formed downstream the platelets along with the flow as a result of shear forces, and the formation depends on the activation of cyclophilin D, calpain, and small GTPase Rac1. Circulating monocytes and neutrophils interact with these membrane extensions and capture membrane fragments, thereby generating platelet microparticle–monocyte and microparticle–neutrophil complexes and subsequent activation of monocytes and neutrophils. We propose that this mechanism of platelet membrane retrieval may be relevant for the platelet contribution in the progression of inflammatory diseases. Further studies are required to determine to what extent in vivo FLIPR formation contributes to the platelet contribution in inflammation.

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Disclosures

None.

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Novelty and Significance

What Is Known?

- Platelets are important in both hemostasis and inflammation.
- Activated platelets have procoagulant activity and generate microparticles.
- Activated platelets are, furthermore, able to bind leukocytes, thereby promoting inflammatory responses.

What New Information Does This Article Contribute?

- Activated platelets under flow generate extremely long membrane protrusions.
- These protrusions can sever as a result of shear, resulting in the formation of platelet microparticles.
- Leukocytes are able to bind to the long membrane strands resulting in leukocyte activation.

The dynamic process leading to procoagulant and proinflammatory platelet formation has never been visualized. We, therefore, aimed to visualize this dynamic process under physiological flow. Exposing platelets to shear and agonists results in the formation of flow-induced protrusions (FLIPRs), both in vitro as well as in a mouse carotid injury model in vivo. Severing of FLIPRs from adhered platelets results in the formation of microparticles and balloon-shaped platelets. Balloon-shaped platelets have been demonstrated previously and are known to exhibit procoagulant and proinflammatory properties. Previous studies, furthermore, show the importance of mitochondrial calcium regulation for the generation of procoagulant activity and the requirement for calcium-dependent protease calpain in the generation of microparticles. We show that both are also required for FLIPR formation. In addition, monocytes and neutrophils are able to roll over FLIPRs and retrieve membrane fragments as microparticles on their surface. This results in the activation of monocytes and neutrophils, promoting the inflammatory response. FLIPR formation, as presented in our current study, provides a mechanistic model for platelet membrane transfer and generation of monocyte/neutrophil–microparticle complexes. We propose that the formation of FLIPRs in vivo contributes to the well-established proinflammatory function of platelets and platelet-derived microparticles.

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