Signaling During Platelet Adhesion and Activation

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Abstract—Upon vascular injury, platelets are activated by adhesion to adhesive proteins, such as von Willebrand factor and collagen, or by soluble platelet agonists, such as ADP, thrombin, and thromboxane A2. These adhesive proteins and soluble agonists induce signal transduction via their respective receptors. The various receptor-specific platelet activation signaling pathways converge into common signaling events that stimulate platelet shape change and granule secretion and ultimately induce the “inside-out” signaling process leading to activation of the ligand-binding function of integrin αIIbβ3. Ligand binding to integrin αIIbβ3 mediates platelet adhesion and aggregation and triggers “outside-in” signaling, resulting in platelet spreading, additional granule secretion, stabilization of platelet adhesion and aggregation, and clot retraction. It has become increasingly evident that agonist-induced platelet activation signals also cross talk with integrin outside-in signals to regulate platelet responses. Platelet activation involves a series of rapid positive feedback loops that greatly amplify initial activation signals and enable robust platelet recruitment and thrombus stabilization. Recent studies have provided novel insight into the molecular mechanisms of these processes. (Arterioscler Thromb Vase Biol. 2010;30:2341-2349.)

Key Words: adhesion molecules ★ G proteins ★ platelets ★ receptors ★ signal transduction

Blood platelets play important roles in hemostasis, thrombosis, wound healing, atherosclerosis, inflammation, immunity, and tumor metastasis.1–4 Of these functions, the primary physiological function of platelets is to form hemostatic thrombi that prevent blood loss and maintain vascular integrity. This function must be tightly regulated because dysregulated thrombus formation (thrombosis) causes blockage of blood vessels, leading to ischemia. Thrombotic diseases, such as heart attack and ischemic stroke, are a leading cause of mortality in the modern world. Thus, platelets in normal circulation are in a nonadherent “resting” state and become activated at sites of vascular injury after exposure to immobilized adhesive proteins or soluble platelet agonists. The signaling process that occurs during platelet activation can be classified into 3 stages: (1) the interaction of agonists with their respective platelet receptors and receptor-mediated early platelet activation signaling, (2) the intermediate common signaling events, and (3) integrin activation (inside-out signaling) and outside-in signaling. However, platelet activation is a dynamic process involving multiple feedback loops and cross talk between different pathways. In particular, platelets rely on endogenous secondary signal amplification mechanisms and their regulation to achieve a relevant level of response to vascular injury.

In the past 3 decades, remarkable progress has been made in identifying the fundamental mechanisms of platelet function and signaling pathways of platelet activation, which has greatly facilitated the development of antiplatelet therapeutics for preventing and treating thrombotic diseases.1,2 However, the agents that block fundamental platelet functions, such as integrin blockers, while having potent antithrombotic effects, cause bleeding in approximately 0.5% to 1.5% of patients receiving such compounds. The cyclooxygenase inhibitor (aspirin) and ADP purinergic receptor P2Y12 antagonists in use are also associated with problems such as drug resistance and bleeding. A better understanding of intracellular signaling during platelet adhesion and activation will be helpful for the development of new generations of antiplatelet therapies.

Adhesion Receptor–Mediated Platelet Activation and Signaling

Platelet adhesion receptors are the key initiators of platelet activation at sites of vascular injury where platelets become exposed to adhesive proteins in the matrix or on endothelial cells (Figure 1). Interestingly, despite significant differences in their functions and signaling pathways, several major platelet adhesion receptors share many similarities in their signal transduction mechanisms. For example, signal transduction through the glycoprotein Ib–IX-V complex (GPIb-IX), GPVI, and integrins all involve Src family kinases (SFKs), phosphoinositide 3-kinases (PI3Ks), and the immunoreceptor tyrosine-based activation motif (ITAM) signaling pathway.

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von Willebrand Factor/GPib-IX–Mediated Platelet Activation

Under high shear rate flow conditions present in arteries and arterioles, initial platelet adhesion requires the binding of immobilized von Willebrand factor (VWF) to its platelet receptor, GPib-IX. VWF forms a so-called “catch bond” or “flex bond” with the ligand-binding domain of GPib-IX, allowing transient platelet adhesion under high shear stress. VWF/GPib-IX interaction also induces platelet activation signaling events, leading to integrin activation and integrin-dependent stable platelet adhesion and aggregation. In addition, GPib-IX binds thrombin and sensitizes platelets to low-dose thrombin.

There has been evidence that GPib-IX is associated with the ITAM receptors FcγRIIA or FcγRIIc. Genetic deletion of ITAM signaling molecules, such as FcγRI, Syk, LAT, SLP-76, and Btk, abolishes the TXA2 and secretion-dependent second wave of platelet aggregation induced by VWF/botrocetin in washed mouse platelets. However, loss of FcγRI and LAT does not appear to affect GPib-IX–dependent integrin activation and TXA2 synthesis, both of which involve the mitogen-activated protein kinase (MAPK) pathway. Similarly, Syk is not required for GPib-IX– and integrin-dependent stable platelet adhesion to VWF under shear stress. Considering the importance of the ITAM pathway in granule secretion and integrin outside-in signaling, it likely functions as an important signal amplification mechanism in GPib-IX signaling.

The cytoplasmic domain of the GPibα chain reportedly interacts with SFKs and PI3Ks, which are important for transmitting the “early” activation signals from GPib-IX leading to calcium elevation and integrin activation independent of other receptors. The SFK Lyn is required for activation of PI3K and its downstream effector Akt, leading to integrin activation. Interestingly, VWF/GPib-IX interaction induces elevation of intracellular cGMP levels and sequential activation of cGMP-dependent protein kinase (PKG) and the MAPKs, which may play an important role in GPIb-IX–mediated integrin activation and TXA2 synthesis.

The cGMP signaling pathway is activated downstream from the Lyn/PI3K/Akt pathway, which activates NO synthase. NO may be important for VWF-induced cGMP elevation, although SFK-dependent NO-independent soluble guanylyl cyclase activation has been proposed. A role for the PKG/MAPK signaling pathway in GPib-IX–mediated integrin activation has been shown using inhibitors and knockout mice. Together, these data reveal that the Lyn/PI3K/Akt/NO/cGMP/PKG/MAPK signaling pathway plays an important role in GPib-IX–mediated platelet activation. The role of NO and cGMP in platelet activation is biphasic. The low concentrations of NO/cGMP synthesized during platelet activation are stimulatory, whereas high concentrations of NO and cGMP inhibit platelet activation. The biphasic role of the NO/cGMP pathway may serve to stimulate robust hemostatic thrombus formation at sites of vascular injury while preventing overgrowth of the thrombus.
Platelet Activation and Signaling Mediated by G-Protein–Coupled Receptors

A variety of soluble platelet agonists are released from damaged cells (eg, ADP), produced in coagulation (eg, thrombin) and inflammation (eg, platelet-activating factor), and enriched in atherosclerotic plaques (eg, lysophosphatidic acid). They play a critical role in platelet activation and thrombus formation.38 Equally important, soluble platelet agonists, such as TXA2, ADP, and serotonin, are released from stimulated platelets that serve to amplify platelet activation and recruit circulating platelets. These agonists activate platelets via G-protein–coupled receptors (GPCRs), a family of 7-transmembrane domain receptors that transmit cellular signals through heterotrimeric G proteins (Figure 2).

The heterotrimeric G proteins consist of 3 subunits (α, β, and γ) that bind to GPCRs in an α/β/γ complex. On receptor ligation, the α subunit is converted from a GDP-bound form to the active GTP-bound form. Activated Go subunits dissociate from the receptor, and from the β/γ complex, and interact with specific downstream targets to transmit GPCR signals.38 The β/γ complex can also interact with and activate downstream effectors, including PI3Kγ.39 Based on the similarity of α subunits, G proteins can be divided into 4 subfamilies: Gq/G11, G12/G13, Gi/Go/Gz, and Gs, each of which is coupled to selective receptors and downstream effectors (Figure 2).38 Platelets express Gq, G12/G13, Gi/Gz, and Gs. G proteins in platelets are coupled to agonist receptors that stimulate platelet activation, with the exception of Gs, which is coupled to receptors for physiological platelet inhibitors (prostacyclin and adenosine) that mediate inhibitory signals by stimulating adenyl cyclase–dependent cAMP synthesis (Figure 2). Thrombin-induced platelet activation is mediated via a dual system of G-protein–coupled protease-activated receptors (PARs): PAR1 and PAR4 in humans40 and PAR3 and PAR4 in mice.41 PAR3 appears to sensitize PAR4 to thrombin,42,43 PAR1 and PAR4 directly couple to Gq and G12/G13 and possibly to G11.44,45 TXA2 activates platelets via the TXA2/prostaglandin H2 receptor (TP), which couples to Gq and G13.36,37 Serotonin (5-hydroxytryptamine, 5HT) recognizes the Gq-coupled receptor 5HT2A.38 ADP induces platelet activation via P2Y1 (Gq coupled) and P2Y12 (Gi coupled).38,48 The epinephrine receptor (α2) in platelets is reportedly coupled to Gz, another Gi subtype.49

Gq-Mediated Signaling

Gq transmits cellular signals mainly through its interaction and stimulation of PLCβ. Gq signaling is important for GPCR-stimulated platelet granule secretion, integrin activation, and consequent platelet aggregation.50 Deletion of Gq causes defects in platelet secretion and aggregation in response to a variety of agonists, including thrombin, ADP, TXA2 analogue U46619, and even collagen (probably because of the dependence of the collagen signaling pathway on TXA2).50 In addition, Gq is important in ADP-induced platelet shape change,50 probably by stimulating calcium/calmodulin- and/or RhoA-dependent contractile signaling.51

Gi-Mediated Signaling

Although Gq is required for platelet activation induced by GPCR agonists, it is neither sufficient for platelet aggregation induced by ADP nor for optimal platelet response induced by TXA2 or low-dose thrombin. The Gi-coupled ADP receptor, P2Y12,52,53 is also required for ADP-induced platelet activation and promotes platelet activation induced by TXA2 and low-dose thrombin.45,54 However, it remains controversial whether the thrombin receptors are coupled to Gi directly or indirectly via P2Y12.44,45 The role of Gi-coupled receptors in promoting platelet activation is consistent with the inhibitory effect of Gi on cAMP synthesis, which relieves the inhibitory effect of cAMP-dependent protein kinase on platelet activation. More important, P2Y12-coupled Gi is a major mechanism responsible for the activation of PI3K, particularly β/γ subunit–activated PI3Kγ, in platelets55,56 and subsequent activation of the small GTPase Rap1b,57,58 a critical mediator of integrin activation.

G13 Signaling

Platelets express both Ga12 and Ga1359; however, only Ga13-knockout platelets show reduced and unstable platelet aggregation induced by low-dose thrombin and the TXA2 analogue U46619. Ga13-knockout platelets have reduced granule secretion that is induced by U46619 but not thrombin.50 Shape change induced by these agonists is also reduced in Ga13-knockout platelets. GTP-bound Ga13 interacts with and activates guanine nucleotide exchange factors (GEFs) for the small G protein RhoA, such as p115RhoGGEF, which subsequently converts RhoA into the active GTP-bound form.60 RhoA activates Rho kinase, which phosphorylates and inhibits myosin light chain phosphatase,61 thus enhancing
myosin light chain phosphorylation and myosin light chain–dependent contraction. Therefore, G13 stimulates platelet shape change and granule secretion.62 Interestingly, Ga13 deficiency causes more dramatic defects in platelet adhesion and in hemostasis and thrombosis in vivo, relative to its effects on integrin activation, aggregation, and granule secretion in vitro, suggesting an additional role of Ga13 in platelet function.60 Indeed, Ga13 binds to the cytoplasmic domain of integrin β3 and plays a critical role in integrin outside-in signaling.63

Common Platelet Activation Signaling and Amplification Pathways

Although the initial signaling mechanisms of various platelet receptors differ, they ultimately converge into common intracellular signaling events. In particular, almost all agonists induce activation of PLC. For example, PLCγ and PLCβ are activated by the ITAM and Gq pathways, respectively.64 PLC catalyzes the hydrolysis of phosphatidylinositol 4,5-bisphosphate to release inositol trisphosphate (IP3) and diacylglycerol (DAG), which activate calcium mobilization and protein kinase C (PKC), respectively. Intracellular calcium and DAG together also activate calcium and DAG-regulated GEF 1 (CalDAG-GEFI), a Rap1 GEF important in integrin signaling.65

Calcium Signaling

The critical role of cytosolic calcium in platelet activation and function has been known for many years. Agonist-induced calcium elevation is mainly induced by inositol trisphosphate receptor-mediated release of calcium from intracellular stores and store-operated calcium entry from outside of platelets.66,67 A role for store-independent calcium entry has also been shown.66 Canonical transient potential channels and the calcium release–activated channel (Orai1) have been shown to mediate calcium entry.66,67 Elevation of calcium levels activates multiple signaling events and molecules, including actin–myosin interaction, PKC, calmodulin, NO synthases, and calcium-dependent proteases. Recently, CalDAG-GEFI has mediated several important Ca2+ responses, including Rap1 activation, extracellular signal–regulated kinase activation, TXA2 synthesis, and granule secretion.67 Calcium elevation also positively regulates SFKs and the PI3K/Akt signaling pathway.68

Protein Kinase C

Platelets express several isoforms of the PKC family, including the classical (or conventional) PKC isoforms α and β (calcium and DAG dependent), the novel PKC isoforms δ, θ, and η (DAG dependent and calcium independent), and an atypical PKC isoform ξ (calcium and DAG independent).69–73 Another novel PKC, PKC ε, is detectable in mouse, but not human platelets.74 Classical PKCs, particularly PKC α, play a critical and general role in platelet granule secretion and secretion-dependent aggregation. PKC α has also been shown to regulate Rap1 and integrin signaling in a reconstituted Chinese hamster ovary cell model.75 PKC δ and θ promote dense granule secretion in response to thrombin receptor agonists69,71,72; however, their roles in GPVI-mediated secretion and aggregation are controversial. PKC δ has been reported to negatively regulate GPVI-induced dense granule secretion69,72 or to have no effect.73 PKC θ has been shown to promote GPVI-dependent platelet granule secretion and aggregation by one group,71 but to negatively regulate GPVI-mediated granule secretion and platelet activation by other groups.76,77 Pleckstrin is a major PKC substrate and may possibly be involved in cytoskeleton regulation.78

Signals Leading to Granule Secretion and Secretion-Dependent Signal Amplification

A common platelet response to all agonists is the secretion of granule contents. Platelets contain 3 major types of granules: α-granules, containing adhesion proteins (eg, fibrinogen, VWF, coagulation and fibrinolytic factors, cytokines, growth factors, and adhesion receptors); dense granules, containing nucleotides (eg, ADP, ATP, and GTP; serotonin; histamine; pyrophosphates; and divalent cations); and lysosomes, containing a host of proteolytic enzymes.79 Granule secretion plays critical roles in the amplification of platelet activation, the recruitment of circulating platelets into aggregates, and thrombus stabilization.79,80 Thus, it can be considered a signaling amplification mechanism. Granule secretion also plays important roles in inflammation, atherosclerosis, host defense, wound healing, angiogenesis, and malignancy.81 Granule secretion requires fusion between plasma and granule (vesicle) membranes, which is mediated by protein complexes of vesicle-soluble N-ethylmaleimide–sensitive fusion protein attachment receptor (v-SNARE) proteins (mainly vesicle associated membrane protein [VAMP]-8 in platelets) and plasma membrane (target)–SNARE (mainly syntaxin and synaptosome-associated protein-23 in platelets), as reviewed elsewhere.79 The interaction between SNARE proteins is regulated by their phosphorylation and involves small GTPases, such as Rab27. There are multiple signaling events and pathways that are important in stimulating granule secretion: (1) calcium signaling; (2) PKC-dependent phosphorylation and regulation of SNARE complexes76; (3) integrin outside-in signaling; (4) TXA2 generation, which is important in granule secretion induced by ADP, VWF, and collagen; (5) signaling via the small GTPases Rac-1 and RhoA82,83; (6) activation of SFKs, particularly Lyn84,85; (7) the PI3K/Akt signaling pathway56,86–89; (8) the NO/cGMP/PKG pathway90,91; and (9) the signaling pathways of MAPK isoforms p38, ERK, and JNK.92–95 Recent studies suggest that SFK Lyn activates the PI3K/Akt pathway.85 PI3K and Akt mediate granule secretion primarily by activating the NO/cGMP/PKG pathway, which stimulates granule secretion through the activation of MAPKs and phosphorylation of SNARE proteins.90–92

Integrin Signaling

Inside-Out Signaling

Platelets express integrins αIβ3 (fibrinogen receptor), αIβ3 (vitronectin receptor), αIβ3 (collagen receptor), αIβ3 (fibronectin receptor), and αIβ3 (laminin receptor). These integrins share similar signal transduction mechanisms. The most abundant integrin in platelets, αIβ3, is normally kept in a resting or low-affinity state in circulating platelets, but transforms into a high-affinity “activated” state after platelet
activation. Activated $\alpha_{\text{IIb}}\beta_3$, by binding to its ligands (fibrinogen, VWF, and many matrix proteins containing RGD-like sequences), mediates stable platelet adhesion, platelet aggregation, and thrombus formation. The integrin–proximal intracellular signaling mechanism that induces changes in the extracellular ligand binding domain of integrins from a “low-affinity” state to the activated state is referred to as “inside-out” signaling. Inside-out signaling requires the binding of talin and kindlins to the cytoplasmic domain of $\alpha_{\text{IIb}}$. The relationship between talin and kindlins in inside-out signaling is still being clarified. The binding sites in the $\alpha_{\text{IIb}}$ cytoplasmic domain for talin and kindlins appear distinct. Talin binds to the membrane proximal region and the NPLY motif of $\alpha_{\text{IIb}}$, whereas kindlins bind to the sequences around the C-terminal NXXY motif. Recent studies support the hypothesis that kindlins regulate talin-integrin interaction and cooperate with talin to stimulate inside-out signaling. The binding of talin head domain to $\beta_3$ appears to be sufficient to trigger disruption of the interaction between the membrane proximal regions of the cytoplasmic domains of $\alpha_{\text{IIb}}$ and $\beta_3$, and conformational changes in $\alpha_{\text{IIb}}\beta_3$ that propagate to the extracellular ligand-binding domain, transforming integrin $\alpha_{\text{IIb}}\beta_3$ into the “active” conformation. The change of conformation in $\alpha_{\text{IIb}}\beta_3$ from a bent to an extended form may result in the activation of the ligand-binding function of the integrin. A possible role of integrin transmembrane domain interactions in this process has also been suggested.

Recent studies suggest that CalDAG-GEF1 and its downstream target, Rap1, play an important role in inside-out signaling. CalDAG-GEF1 converts Rap1, a member of the Ras family of small GTases, from the GDP-bound form to the active GTP-bound form, which interacts with the Rap1-GTP–interacting adaptor molecule (RIAM). The role of CalDAG-GEF1/Rap1 in integrin inside-out signaling is consistent with the data that RIAM promotes $\alpha_{\text{IIb}}\beta_3$-talin interaction and integrin activation. The predominant Rap1 isoform expressed in platelets is Rap1b. However, platelets lacking Rap1b show only partial defects in $\alpha_{\text{IIb}}\beta_3$-dependent platelet aggregation, suggesting that neither Rap1b nor CalDAG-GEF1 is fully responsible for inside-out signaling. It remains to be determined whether other isoforms of CalDAG-GEF1 and Rap1 or alternative pathways are also important in inside-out signaling.

**Outside-In Signaling**

Ligand binding to integrin $\alpha_{\text{IIb}}\beta_3$ mediates platelet adhesion and aggregation and initiates a series of intracellular signaling events ("outside-in" signaling), leading to platelet spreading, granule secretion, stable adhesion, and clot retraction. After ligand binding, integrins undergo “a ligand-induced conformational change” that can be propagated outside-in to the cytoplasmic domain. However, although ligand-induced conformational changes of $\alpha_{\text{IIb}}\beta_3$ occur on the binding of multimeric macromolecular ligands, such as fibrinogen, or monomeric peptide ligands, such as RGDS, a significant cellular response only occurs with multimeric macromolecular ligands, suggesting that ligand-induced re-
Cross Talk Between GPCR Signaling and Integrin Outside-In Signaling

Integrin outside-in signaling amplifies platelet responses to GPCR agonists. Conversely, GPCR signaling promotes integrin outside-in signaling. For example, platelet spreading on fibrinogen is greatly enhanced when platelets are treated with GPCR agonists. This is because GPCRs induce integrin activation and directly regulate integrin outside-in signaling. In particular, GPCR-mediated activation of Gα13, although not directly responsible for integrin activation, greatly enhances the interaction of Gα13 with β3, which is required for outside-in signaling. More important, the GPCR/Gα13 and integrin outside-in signaling pathways coordinate with each other to dynamically regulate RhoA-dependent signaling in platelets. The ability of these 2 signaling pathways to cross talk and dynamically regulate RhoA-dependent signaling is critical for the processes of shape change, granule secretion, spreading, and clot retraction in platelets (Figure 3).

Conclusions

Significant progress has been made in recent years in our understanding of platelet signal transduction during adhesion and activation. Thus, we face an increasingly complex signaling network in platelets and new frontiers to be explored. Many new opportunities for discovery lie in the molecular details of the apparently well-defined signaling pathways. With the goal of fighting thrombotic and hemorrhagic diseases in mind, it is intriguing to know whether further dissection of the molecular mechanisms of integrin signaling may lead to the development of new inhibitors that specifically inhibit outside-in signaling-mediated amplification of platelet activation and platelet recruitment without blocking the ligand-binding function of integrins critically important in hemostasis. Also, the importance of the cross talk between various adhesion receptor signaling pathways and G-protein–coupled signaling pathways is increasingly evident. Understanding the cross talk between these pathways may provide insight into the phenomenon of “resistance” to existing platelet inhibitors and may allow for the development of new therapeutic agents that are more effective in treating thrombosis, with less bleeding side effect. Finally, the elucidation of platelet signaling pathways that contribute to the functions of platelets in events beyond hemostasis and thrombosis, such as those discussed in other articles in this series, may reveal new therapeutic targets for the treatment of disorders such as inflammatory diseases, atherosclerosis, and cancer.

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Disclosures

Dr Du, University of Illinois, Chicago, holds patents relevant to the topic of this review.

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