Integrated Signaling: The Platelet Paradigm

By Sanford J. Shattil, Hirokazu Kashiwagi, and Nisar Pampori

ADHESION IS REQUIRED for cell growth, differentiation, survival, and function. Nowhere is this more evident than in the response to tissue injury, where vascular damage triggers reparative processes, such as hemostasis, inflammation, and wound healing. These processes depend on a coordinated series of cell adhesion and migration events by platelets, leukocytes, and vascular cells for their successful execution.3 Cell adhesion is mediated by a structurally diverse group of plasma membrane receptors, each exhibiting specialized ligand-binding properties that are needed for specific tasks in the injury response. For example, when blood flows through a damaged blood vessel, leukocytes slow down and roll on the endothelial surface as a consequence of the interaction of appropriate sialyl Lewis X-rich membrane glycoproteins on the leukocytes with selectins on the endothelial cells.2-3 Platelets also roll under conditions of high shear on perturbed endothelium2 as well as on denuded vascular surfaces, in the latter case through interactions of the platelet glycoprotein (GP) Ib-V-IX complex with von Willebrand factor (vWF) in the subendothelial matrix.4 Once the rolling process has slowed down these blood cells, they come to an abrupt stop at the right place through regulated interactions between integrin adhesion receptors and either counter-receptors on endothelial cells or adhesive proteins in the matrix.2,5 Integrins also mediate responses necessary for eventual completion of the injury response, including leukocyte transmigration and platelet aggregation.6

Although adhesion receptors rightfully deserve this moniker, any implication that they are simply cellular velcro is incorrect. Most, if not all, adhesion receptors engage in a dialogue with the extracellular and intracellular milieu. Integrins are a case in point. Cells often regulate ligand binding to integrins through a process known as inside-out signaling or integrin activation. Furthermore, once integrins have become occupied and clustered by their ligands, they can diffuse laterally within the plasma membrane, inside-out signaling denotes reactions initiated by integrin binding to regulatory proteins in the matrix.2,5 Integrins also mediate responses necessary for eventual completion of the injury response, including leukocyte transmigration and platelet aggregation.6,26

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WHAT IS INTEGRIN SIGNALING?

\(\alpha_{\text{IIb}}\beta_3\) consists of a two-chain \(\alpha\) subunit bound noncovalently to a single-chain \(\beta\) subunit. Each subunit spans the platelet membrane once. The N-terminus and most of the remainder of each subunit are extracellular, and the membrane-spanning domain is connected to a short C-terminal cytoplasmic tail consisting of 20 amino acid residues in \(\alpha\text{IIb}\) and 47 residues in \(\beta_3\). Electron microscopy of heterodimers shows an N-terminal globular head connected to two C-terminal stalks.15,16 Although the atomic structure of \(\alpha_{\text{IIb}}\beta_3\) is not known, biochemical, genetic, and molecular modeling studies indicate that ligand binding is primarily a function of the globular heads.17 Because ligand binding is regulated by signals from within the platelet and also triggers platelet responses, mechanisms must exist to propagate information back and forth between the cytoplasmic tails and the globular heads. This overall process is referred to as integrin signaling.

A didactic distinction is often made between inside-out and outside-in signaling. Inside-out signaling denotes those reactions initiated by the binding of one or more agonists to their plasma membrane receptors, leading to the conversion of \(\alpha_{\text{IIb}}\beta_3\) from a low-affinity/avidity receptor to a high-affinity/avidity receptor. This conversion has profound consequences in that it determines whether \(\alpha_{\text{IIb}}\beta_3\) can engage soluble adhesive ligands, such as fibrinogen and vWF, which contain a classical integrin recognition sequence, Arg-Gly-Asp. These multivalent ligands can function as bridges between receptors on adjacent platelets, thus allowing platelet aggregation to proceed.18 Because \(\alpha_{\text{IIb}}\beta_3\) can diffuse laterally within the plasma membrane, inside-out signaling can have two distinct components that are often difficult to distinguish in practice: (1) affinity modulation, which implies a structural change intrinsic to the heterodimer that results in a greater strength of ligand binding; and (2) avidity modulation, which implies a change in the functional affinity of the interaction between receptor and ligand due to chelate or rebinding effects.19 One plausible way that the latter could occur is through integrin clustering within the plane of the plasma membrane (Fig 2). Outside-in signaling denotes reactions initiated by integrin ligation and clustering, and these must be coordinated with signals emanating from other plasma membrane receptors (eg, growth factor, cytokine, and G-protein–linked receptors).10,20,21 Integrin signals help to regulate a host of postligand binding events, the particular pattern varying with the cell and the integrin. Postligand binding events regulated by \(\alpha_{\text{IIb}}\beta_3\) in platelets include the stabilization of large platelet aggregates, platelet spreading, granule secretion, clot retraction, and possibly platelet procoagulant activity.22

INSIDE-OUT SIGNALING IN PLATELETS

Resting platelets contain about 80,000 surface copies of \(\alpha_{\text{IIb}}\beta_3\), with additional pools of \(\alpha_{\text{IIb}}\beta_3\) in the membranes of...
The binding of soluble ligands to αIIbβ3 can be detected within seconds of platelet activation, and it reaches a steady-state within minutes. Although ligand binding is at first reversible, it becomes progressively irreversible. Purified αIIbβ3 can bind fibrinogen with a stoichiometry up to 1:1, but the stoichiometry may be lower in platelets. Although ligand-binding to surface-expressed αIIbβ3 is essential for initial, primary platelet aggregation, the internal pools of αIIbβ3 can become exposed after cell activation and participate in the secondary phase in which larger platelet aggregates are formed. In fact, the α-granule membrane pool of αIIbβ3 may already be complexed with fibrinogen stored within these granules. Should the surface pool of receptors on resting platelets become unavailable to bind ligand, as for example after infusion of a function-blocking antibody, the α-granule pool may be able to support platelet aggregation.

Affinity versus avidity modulation. Platelets and other cells use a conformational switch mechanism (affinity modulation) and receptor clustering (avidity modulation) to regulate ligand binding to integrins, and the relative contribution of each varies with the integrin and the cell type. Available evidence indicates that the initial, reversible phase of ligand binding to αIIbβ3 is due to affinity modulation, whereas the irreversible phase may be due to several factors, including (1) ligand-induced changes intrinsic to the receptor (perhaps analogous to those responsible for induced fit between an antibody and antigen); (2) receptor clustering; and (3) receptor internalization. In addition, thrombospondin and other substances released from α-granules during secretion may bind to fibrinogen and/or αIIbβ3 and stabilize the ligand-receptor interaction. An initial conformational switch mechanism is consistent with the rapid and selective binding of a monovalent,
The structural changes in αIIbβ3 responsible for interconversion between low- and high-affinity states are not known. One model posits that the signaling reactions triggered by platelet agonists cause some modification of the integrin cytoplasmic tails which is then propagated to the extracellular domains to effect ligand binding (Fig 2). Recent progress has been made in understanding the kinds of structural changes in the globular head of αIIbβ3 that may be required. Based on model building and the functional effects of mutations, Springer et al. have proposed that the N-terminal region of αIIb (and other integrin α subunits) conforms to the shape of a β-propeller with seven blades oriented radially and pseudosymmetrically around a central axis and parallel to the plasma membrane. The ligand binding interface would lie on the top surface of the propeller (Fig 3). Tozer et al. have proposed that a second ligand binding site is located in an N-terminal region of β3 that bears homology with an I-domain, which is, ironically, a ligand-binding module of approximately 190 amino acids inserted within certain α subunits (but not αIIb). Crystallographic analyses of I domains from α1 and αM show an α/β fold consisting of seven α-helices packed against a six-stranded β-sheet. At one end of the β-sheet is a cation binding MIDAS motif implicated in ligand binding (Fig 3).

Based on this information, Loftus and Liddington have proposed a model for the conformational switch in αIIbβ3 that provides a good framework for further studies. It predicts that, in resting platelets, the I-domain–like region in β3 is incapable of binding ligand, but it occludes the ligand binding site in αIIb. Platelet activation would then induce ligand binding by (1) causing a conformational change in the β3 I domain to expose its ligand binding site and (2) changing the orientation of the subunits to unmask the ligand binding site in αIIb. This implies that the receptor may engage discontinuous regions of the ligand, consistent with the fact that each fibrinogen monomer is multivalent with respect to αIIbβ3. For example, the C-terminus of the fibrinogen γ chain is essential for initial binding of the soluble ligand to platelet αIIbβ3, but one or both of the Arg-Gly-Asp sites in the Aα chain may provide secondary points of attachment needed for tighter binding. These Aα sites may also assume importance when the fibrinogen is immobilized on a surface or converted to fibrin.

Reactions that initiate and propagate inside-out signaling. Inside-out signaling involves reactions that (1) initiate and propagate the flow of information from agonist or antagonist receptors to integrin proximal effectors and (2) directly effect integrin activation or deactivation. Currently, only a broad outline of these reactions can be provided.

Inside-out signaling is triggered by many excitatory agonists, some of which, including thrombin, ADP, epinephrine, and thromboxane A3, bind to heptahelical receptors coupled to heterotrimeric (αβγ) G proteins. In the case of some of these agonists, one consequence important for inside-out signaling is activation of phospholipase Cβ by the activated α subunit of Gq, resulting in hydrolysis of phosphatidylinositol and production of the second messengers, diacylglycerol and IP3. Mouse platelets that have been rendered null for Gq undergo
shape change but fail to aggregate in response to thrombin, ADP, or a thromboxane A2 receptor agonist, and the mice exhibit prolonged tail bleeding times.53 Occupancy of many G-protein–coupled platelet receptors also leads to rapid activation of nonreceptor protein tyrosine kinases, including Src, Syk, and Pyk2 (also known as RAFTK or CAKβ).54,55 Although the mechanism by which G proteins couple to tyrosine kinase cascades in platelets has not been characterized, the net result is tyrosine phosphorylation of a number of proteins, including phospholipase Cγ.56 Vav (a guanine nucleotide exchange factor for the Rac GTP-ase), and cortactin (a cortical actin-binding protein).54,57,58 A role for tyrosine phosphorylation-dephosphorylation in integrin activation is suggested by observations that tyrosine kinase inhibitors partially block fibrinogen binding and platelet aggregation, whereas inhibitors of protein tyrosine phosphatases trigger platelet activation.14,54,59 Furthermore, mouse platelets that have been rendered null for Syk show a modest reduction in fibrinogen binding in response to ADP and epinephrine.60 Additional support for a tyrosine phosphorylation-integrin activation connection comes from studies of three agonist receptors that are not known to be coupled to G proteins.

The Fc receptor, FcγRIIA, contains an immune receptor tyrosine activation motif (ITAM) in its cytoplasmic tail. When the receptor is clustered by aggregated Igs, two tyrosines in the ITAM are phosphorylated by a Src family kinase, enabling Syk, which contains tandem SH2 domains, and possibly other ITAM are phosphorylated by a Src family kinase, enabling Syk, the receptor is clustered by aggregated Igs, two tyrosines in the

...
platelets has not been demonstrated. Thrombin stimulation of platelets causes GTP loading of H-Ras in a PKC-dependent manner and of Rap1 in a Ca\(^{2+}\)-dependent manner.

Platelets contain several potential H-Ras effectors, including PI 3-kinase and Raf-1, and thrombin induces activation of MAP (ERK2) kinase in platelets, possibly through the classical H-Ras pathway. When overexpressed in CHO cells, activated H-Ras or Raf-1 can suppress integrin activation. In platelets, the reverse is true: the ERK2 response to thrombin is dampened by fibrinogen binding and aggregation.

Pathways that inhibit \(\alpha_{IIb}\beta_3\) are just as important as those that activate it. Prostaglandin \(I_2\) produced by endothelial cells is a potent platelet activation and aggregation inhibitor that binds to a specific Gs-coupled heptahelical receptor, thereby activating adenyl cyclase and cyclic AMP-dependent protein kinase (PKA). Platelet aggregation is also inhibited by nitric oxide, which is synthesized by both endothelial cells and platelets and activates soluble guanylyl cyclase (PKG). The importance of the nitric oxide inhibitory pathway in vivo is shown by two brothers with a defect in the bioavailability of nitric oxide, heightened platelet reactivity to agonists, and a history of cerebrovascular events. One common substrate of PKA and PKG is VASP, a 50-kD protein that localizes to focal adhesions and regulates actin dynamics. The phosphorylation of VASP on specific serine residues by agents that activate PKA or PKG correlates with inhibition of platelet aggregation. However, PKA and PKG are likely to exert their inhibitory effects on \(\alpha_{IIb}\beta_3\) at several levels of stimulus-response coupling, implying that more than one effector of these serine-threonine kinases is involved. CD39 is an ecto-ADPase on endothelial cells that may be an important regulator of platelet responses to ADP. Platelets express PDGF \(\alpha\)-receptors and store PDGF in their \(\alpha\)-granules. Incubation of platelets with PDGF dampens subsequent aggregation responses to excitatory agonists.

Reactions that effect inside-out signaling. The conformational switch necessary for ligand binding to \(\alpha_{IIb}\beta_3\) could be regulated by intracellular molecules that bind to the cytoplasmic tails of the integrin or by integrin-associated membrane proteins. Evidence directly implicating the cytoplasmic tails in affinity modulation comes from studies of naturally occurring and experimental integrin mutations, from analyses of \(\alpha_{IIb}\beta_3\) function in heterologous expression systems, and from identification of integrin tail-binding proteins. In addition, several membrane proteins have been reported to form complexes with \(\alpha_{IIb}\beta_3\) or other integrins.

The sequences of the cytoplasmic tails of \(\alpha_{IIb}\) and \(\beta_3\) are shown in Fig 4. Two patients with genetic abnormalities in the \(\beta_3\) cytoplasmic tail provide living examples of the importance of this tail in integrin signaling. Both exhibit bleeding disorders of mild to moderate severity due to variant thrombocytopenia: despite near-normal levels of \(\alpha_{IIb}\beta_3\), their activated platelets bind neither fibrinogen nor aggregate. One of these individuals exhibits a point mutation in \(\beta_3\) (\(\beta_3\ S752P\)), the other exhibits a deletion of the 39 C-terminal residues from the \(\beta_3\) tail (\(\beta_3\ D 724\)). In each case, the profound defect in activation of \(\alpha_{IIb}\beta_3\) can be recapitulated by expressing the recombinant mutant in CHO cells. Transfection studies in CHO cells and in a B-lymphocyte cell line have shown that other mutations in the cytoplasmic tails also affect \(\alpha_{IIb}\beta_3\) affinity.

These results can be summarized as follows. Wild-type \(\alpha_{IIb}\beta_3\) exists in a default low-affinity state in these cells, but two different classes of tail alterations lead to a constitutive high-affinity state. One involves deletions or mutations of specific membrane-proximal residues in the \(\alpha_{IIb}\), or \(\beta_3\) tails, causing the receptor to remain in a high-affinity state even if cellular ATP is depleted. The other class involves replacement of the \(\alpha_{IIb}\) tail with certain other tails (eg, \(\alpha_\gamma\) or \(\alpha_\delta\)), but in this case the receptor reverts to a low-affinity state upon depletion of ATP. This class of energy-dependent, high-affinity mutants can also be inhibited by overexpression of isolated \(\beta_3\) cytoplasmic tail chimeras, suggesting that integrin affinity is being regulated by titratable intracellular factors. This idea is supported by the observation that \(\alpha_{IIb}\beta_3\)-dependent adhesion of a megakaryocytic cell line is inhibited by cellular incorporation of peptides derived from the membrane-distal region of the \(\beta_3\) tail.

These results suggest a working model in which the membrane-proximal portions of the \(\alpha_{IIb}\) and \(\beta_3\) tails normally interact, possibly in part through a salt bridge, to form a hinge through which signals impacting on membrane distal tail residues are propagated across the membrane to modulate receptor affinity. Certain membrane-proximal mutations or deletions break this hinge, leaving the receptor in a permanent high-affinity state. Membrane-distal tail residues might regulate receptor affinity in several ways: In unstimulated cells, the \(\alpha_{IIb}\) tail might bind a negative regulator or interact with the \(\beta_3\) tail in such a way as to prevent the action of a positive regulator. In stimulated cells, a change in these relationships would either relieve the negative constraint or trigger the function of the positive regulator. This model predicts close but dynamic interactions between the \(\alpha_{IIb}\) and \(\beta_3\) tails. In fact, synthetic peptides derived from these tails do interact in vitro.

A number of proteins have been shown to bind directly to integrin cytoplasmic tails, at least in vitro (Table 1), but there is no evidence yet that the endogenous forms of any of these proteins modulate integrin affinity in cells. One such protein, \(\beta_3\)-endonexin, binds selectively to the \(\beta_3\) tail and is present in platelets. Overexpression of a \(\beta_3\) endonexin fusion protein in CHO cells increases the affinity state of \(\alpha_{IIb}\beta_3\) and causes

![Fig 4. Amino acid sequences of the cytoplasmic tails of \(\alpha_{IIb}\) and \(\beta_3\). The space inserted into each sequence arbitrarily separates the N-terminal membrane-proximal and C-terminal membrane-distal regions, the significance of which is discussed further in the text. Numbered residues are as in the full-length integrin subunit.](image-url)
fibrinogen-dependent cell aggregation. Although some of the other proteins listed in Table 1 are present in platelets, it is not known if they influence αIIbβ3 affinity. Two proteins listed in the table may not be relevant to αIIbβ3, but they provide potential novel links between integrins and cellular signaling pathways. Cytohesin-1 binds selectively to the β2 integrin tail and when overexpressed in T lymphocytes, it increases cell adhesion through αIIbβ2. Cytohesin-1 contains a PH domain, which binds 3-phosphorylated phosphoinositides, and a sec 7 domain, which binds the β2 tail and possesses guanine nucleotide exchange activity for a small GTP-ase, ARF. One serine-threonine kinase, p59ILK has been shown to bind to integrin αIIbβ3 and to promote anchorage-independent cell cycle progression and growth of epithelial cells. These studies suggest that, in some cases, integrins may be direct targets of protein kinases, phosphatases, or GTPases. In this regard, the β3 cytoplasmic tail does become phosphorylated on serine, threonine, and tyrosine residues in thrombin-stimulated platelets. However, the stoichiometry and functional significance of these events are not clear. Furthermore, the tyrosine phosphorylation of β3 is dependent on platelet aggregation; therefore, it may be likely to play some role in outside-in signaling.

Several transmembrane or GPI-linked membrane proteins have been shown to either communoprecipitate with integrins or colocalize with them by fluorescence microscopy (Table 2). These associations may be direct or indirect, and several are relevant to αIIbβ3. CD47, also known as integrin-associated protein, spans the platelet plasma membrane five times and communoprecipitates with β3 integrins. So far, no direct role for CD47 in αIIbβ3 function has been demonstrated, either in platelets or in the CHO cell model system. However, CD47 may function as a costimulatory agonist receptor in platelets because binding of thrombospondin to CD47 leads to activation of αIIbβ3 in a Gβ-dependent manner. CD98, a type II transmembrane protein implicated in neutral amino acid transport and viral syncytia formation, was recently identified in a genetic screen by its ability to complement dominant suppression of αIIbβ3 activation in CHO cells, but its abundance in platelets is not known. CD9, a member of the tetraspanin family of transmembrane proteins, colocalizes with αIIbβ3 in platelet α-granule membranes and filopodia. Antibodies to CD9 can stimulate platelet aggregation in an Fc receptor-independent manner. However, tetraspanins may exist in multimolecular complexes, and the interaction of CD9 with αIIbβ3 may not be direct. There is similar uncertainty in interpreting the reported associations of integrins with caveolin or other proteins, such as

### Table 1. Integrin Tail-Binding Proteins

<table>
<thead>
<tr>
<th>Protein</th>
<th>Integrin Tail Partner</th>
<th>Notable Features</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calreticulin</td>
<td>α*</td>
<td>Expression correlates with integrin-mediated cell adhesion; present in many subcellular locations.</td>
<td>173-176</td>
</tr>
<tr>
<td>F-actin</td>
<td>α2 only</td>
<td>Structural cytoskeletal protein</td>
<td>177</td>
</tr>
<tr>
<td>Calcium- and integrin-binding protein (CIB)</td>
<td>α6β1 only</td>
<td>Sequence homology to calcineurin B; contains 2 EF-hand motifs</td>
<td>178</td>
</tr>
<tr>
<td>Talin</td>
<td>αβ6; β</td>
<td>Structural cytoskeletal protein</td>
<td>179, 180</td>
</tr>
<tr>
<td>a-Antinixin</td>
<td>β</td>
<td>Structural cytoskeletal protein</td>
<td>181</td>
</tr>
<tr>
<td>Skeletin</td>
<td>β</td>
<td>A myosin and intermediate filament-associated protein</td>
<td>182</td>
</tr>
<tr>
<td>pp125Syk (focal adhesion kinase)</td>
<td>β</td>
<td>Protein tyrosine kinase localized to focal adhesions</td>
<td>183</td>
</tr>
<tr>
<td>p59ILK (integrin-linked kinase)</td>
<td>β</td>
<td>Contains ankyrin repeats and serum threonine kinase domain; overexpression inhibits cell adhesion and induces anchorage-independent growth</td>
<td>184</td>
</tr>
<tr>
<td>Paxillin</td>
<td>β1</td>
<td>Adapter with SH2 and SH3 binding motifs and LIM domains</td>
<td>185</td>
</tr>
<tr>
<td>ICAP-1</td>
<td>β1 only</td>
<td>Cell adhesion via β1 modulates phosphorylation state of ICAP-1</td>
<td>186</td>
</tr>
<tr>
<td>Filamin</td>
<td>β2</td>
<td>Structural cytoskeletal protein</td>
<td>187</td>
</tr>
<tr>
<td>Cytohesin-1</td>
<td>β2 only</td>
<td>Contains Sec7 and PH domains; guanine nucleotide exchange activity for ADP-ribosylation factor; overexpression increases αIIbβ3-mediated adhesion</td>
<td>121, 123</td>
</tr>
<tr>
<td>β2-endorphin</td>
<td>β3 only</td>
<td>Overexpression increases αIIbβ3 affinity and adhesive function</td>
<td>118, 120</td>
</tr>
<tr>
<td>p27Kip</td>
<td>β4</td>
<td>May link β4 to the intermediate filament cytoskeleton in epithelial cells</td>
<td>188</td>
</tr>
<tr>
<td>Rack 1</td>
<td>β3; β2; β5</td>
<td>Binds to the β tails via its 5-7th WD repeats in response to cell stimulation with phorbol ester</td>
<td>202</td>
</tr>
</tbody>
</table>

*Unless specified otherwise, the integrin-binding protein has been shown to bind to more than type of α or β subunit.


### Table 2. Membrane Proteins Associated With Integrins

<table>
<thead>
<tr>
<th>Protein</th>
<th>Associated Integrin</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD47 (integrin-associated protein)</td>
<td>αIIbβ3; αvβ3; leukocyte-response integrin</td>
<td>128, 190</td>
</tr>
<tr>
<td>CD98</td>
<td>αIIbβ3</td>
<td>132</td>
</tr>
<tr>
<td>Tetraspanins</td>
<td>αvβ3; αvβ5; αvβ1; αvβ3; αvβ5; αvβ1</td>
<td>133, 191-195</td>
</tr>
<tr>
<td>CD9</td>
<td>αIIbβ3</td>
<td>132</td>
</tr>
<tr>
<td>CD63</td>
<td>αvβ3</td>
<td>132</td>
</tr>
<tr>
<td>CD81; NAG-2</td>
<td>αvβ3; αvβ1</td>
<td>132</td>
</tr>
<tr>
<td>CD151</td>
<td>αvβ3</td>
<td>132</td>
</tr>
<tr>
<td>EMMPRIN</td>
<td>αvβ3; αvβ1</td>
<td>196</td>
</tr>
<tr>
<td>Caveolin</td>
<td>αvβ3</td>
<td>135</td>
</tr>
<tr>
<td>CD87 (urokinase plasminogen activator receptor)</td>
<td>αvβ3; αvβ1; αvβ3; αvβ1; αvβ1; αvβ1; αvβ1</td>
<td>197-199</td>
</tr>
<tr>
<td>CD16 (FcRIIIB)</td>
<td>αvβ3</td>
<td>198</td>
</tr>
</tbody>
</table>
Sr family kinases, that may become part of large complexes within lipid-rich membrane microdomains. Thus, the functional and physical relationships between \( \alpha_{\text{IIb}}\beta_3 \) and other proteins remain a fertile area for further investigation.

OUTSIDE-IN SIGNALING IN PLATELETS

Platelet functions regulated by outside-in signaling. Signaling through \( \alpha_{\text{IIb}}\beta_3 \) determines the extent to which platelets spread on a vascular matrix containing vWF or fibrinogen and their resistance to detachment from the matrix. Similarly, outside-in signals triggered during platelet aggregation or spreading promote granule secretion and secondary aggregation. Consequently, outside-in signals are a determinant of the ultimate size of a hemostatic plug or a pathological thrombus (Fig 1). The retraction of a fibrin clot also involves outside-in signals because it represents the interaction of both fibrin and the actin cytoskeleton with \( \alpha_{\text{IIb}}\beta_3 \) and the contraction of actin-myosin. Under certain conditions, even the development of platelet procoagulant activity due to scrambling of membrane phospholipids is dependent, in part, on events subsequent to platelet aggregation.

The temporal and spatial hierarchy of outside-in signaling. Outside-in signaling is initiated at localized regions of cell matrix and cell-cell contact. In the platelet, it is triggered by ligand-induced oligomerization of \( \alpha_{\text{IIb}}\beta_3 \), because only multivalent ligands are capable of inducing the signal. Signaling is propagated by interactions between integrin cytoplasmic tails, signaling molecules, and structural cytoskeletal proteins, including vinculin, talin, and \( \alpha \)-actinin. The initial signaling reactions foster continued assembly of the complex by promoting protein-protein interactions, actin polymerization, and cytoskeletal reorganization. Complex assembly continues until the supply of new components is exhausted or a set of inhibitory signaling reactions takes over, at which time the complex may even disassemble.

The platelet has provided a good model system to study outside-in signaling and cytoskeletal reorganization in the absence of nuclear signaling (Fig 5). Within seconds of binding soluble or immobilized fibrinogen or vWF, platelets extend filopodia coincident with activation of Syk and tyrosine phosphorylation of substrates of 50 to 68 kD and 140 kD. Shortly thereafter, the platelets begin to flatten out or form microscopic aggregates. At this intermediate stage, there is detectable activation of \( \text{pp}60^{\text{Src}} \) and clusters of \( \alpha_{\text{IIb}}\beta_3 \) are discernible by immunofluorescence microscopy on the basal surfaces of the adherent cells. Recent studies in CHO cell transfectants indicate that fibrinogen binding can trigger activation of Syk in a manner that is independent of ITAMs and actin polymerization, due to a combination of autophosphorylation and phosphorylation by Src.

Platelet spreading on fibrinogen or vWF reaches a maximum after several minutes, during which time the platelets display microscopic vinculin clusters connected to \( \alpha \)-actinin cables, the platelet equivalent of focal adhesions. Full spreading or aggregation is associated with activation of the tyrosine kinase, pp125\( ^{\text{FAK}} \), and tyrosine phosphorylation of additional substrates, including proteins of 101 and 105 kD. Tec (a tyrosine kinase that contains a PH domain), and SHIP, an SH2 domain-containing inositol 5-phosphatase. None of these changes occur if spreading or aggregation is blocked. Eventually there is a decrease in tyrosine phosphorylation of many substrates, due to cytoskeletal recruitment and activation of protein tyrosine phosphatases (eg, PTP-1B and SHP-1), and cleavage of protein tyrosine kinases by calpain.

FAK provides a well-studied example of how integrin-associated signaling complexes may assemble. It contains a central catalytic domain flanked by N- and C-terminal domains. Subcellular localization of FAK is dictated by a focal adhesion targeting region in the C-terminal domain and possibly by a binding site for integrin \( \beta \) tails in the N-terminal domain. FAK undergoes autophosphorylation at Y576 in response to cell adhesion, providing a docking site for the SH2...
domain of Src and possibly PI-3-kinase. Src phosphorylates FAK at additional tyrosine residues, creating sites for interaction of the adapter, Grb2. FAK also complexes through proline-rich motifs in the C-terminal domain with the SH3 domains of the adaptors, p130cas and paxillin, and a Rho GTPase-activating protein, GRAF. Indeed, p130cas and paxillin are phosphorylated by the FAK/Src complex, enabling the recruitment of even more proteins. FAK-null mice die in fetal life and, ex vivo, their fibroblasts form focal adhesions but migrate poorly.154 In platelets, activation of FAK requires both αIIbβ3 ligation and agonist receptor occupancy, the latter being required to provide costimulatory signals through Ca2+ and PKC.155

Studies of naturally occurring and experimentally induced mutations and deletions in αIIbβ3 provide strong evidence for involvement of the αIIb and β3 cytoplasmic tails in outside-in signaling.107,108,156 However, many fundamental questions remain. What is the role of tyrosine phosphorylation of the β3 tail in response to platelet aggregation?212 Can certain protein or lipid kinases and phosphatases couple directly to αIIbβ3? What are the effectors of Syk, Src, and FAK? Whereas tyrosine phosphorylation is an early event in outside-in signaling, there is an impressive and growing list of other protein and lipid kinases, phosphatases, phospholipases, and GTP-ases that redistribute to the αIIbβ3-rich core cytoskeleton or become activated during platelet aggregation and spreading.89,144,157-161,203 How are the functions of so many proteins and their effectors integrated into the highly coordinated response to platelet adhesion?

PERSPECTIVE

What are the practical implications of integrin signaling? Integrin cytoplasmic tail mutations in patients with variant thrombasthenia prove that integrin signaling is required for hemostasis, but these patients are very rare. However, other individuals with unexplained platelet aggregation defects are encountered more frequently. Some of these suffer from inherited defects, others from acquired disorders that affect platelet function. Once an aggregation defect has been established in the clinical laboratory, further evaluation can be facilitated by conducting flow cytometry analyses of platelets, even in whole blood. Fluorophore-conjugated reagents are available to quantitate platelet surface antigens, including activation-specific antigens (eg, P-selectin) and epitopes (eg, activated or ligand-occupied αIIbβ3).162 This allows facile categorization of the abnormality as either an αIIbβ3 activation defect or a postligand binding defect.163 In the case of an activation defect, the subsequent work-up can focus on specific agonist receptors and biochemical pathways responsible for inside-out signaling.164-166 In the case of a postligand binding defect, the work-up can focus on the possibility of storage pool disease or an abnormality in pathways triggered by integrin ligation.107,167,168 We speculate that the spectrum of clinical abnormalities in integrin signaling might even include inappropriate increases in αIIbβ3 function. For example, several dominant mutations introduced experimentally into the αIIb or β3 cytoplasmic tails result in constitutive activation of the receptor, as discussed above. If such mutations were to occur naturally, they might be responsible for some cases of unexplained, chronic thrombocytopenia or even represent a risk factor for arterial thrombosis.

Interest in αIIbβ3 has expanded beyond the realm of the hematologist because of the development of pharmacological inhibitors of ligand binding to αIIbβ3 for prophylaxis and therapy of arterial thrombosis.169,170 Abciximab, a chimeric mouse-human antibody that blocks ligand binding to αIIbβ3, is already licensed for use as adjunctive therapy in patients undergoing coronary angioplasty, and additional parenteral and orally active compounds are now in clinical trials. It is too early to predict the full range of indications for these agents or the degree of efficacy and risk of long-term use, but it is satisfying that platelet research has yielded the first integrin-based therapeutics. In this context, the orally active antiplatelet agents currently available in developed countries are, in one way or another, inhibitors of inside-out integrin signaling: aspirin inhibits cyclooxygenase-1 and, ultimately, the production of thromboxane A2; ticlopidine and clopidogrel inhibit signaling through the ADP receptor171; and phosphodiesterase inhibitors decrease catabolism of cyclic AMP, a suppressor of platelet activation. If the intracellular events responsible for αIIbβ3 signaling can be better defined, it may be possible to identify new integrin-proximal signaling proteins as drug targets.

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