DISTINCT ROLE OF PYK2 IN MEDIATING THROMBOXANE GENERATION DOWNSTREAM OF BOTH G_{12/13} AND INTEGRIN αIIbβ3 IN PLATELETS*
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Background: Pyk2 is abundantly expressed in platelets.

Results: Pyk2 regulates TxA_{2} generation induced by both 2-MeSADP and AYPGKF.

Conclusion: Pyk2 is an important functional tyrosine kinase that is activated by both G_{12/13} and integrin αIIbβ3 in platelets.

Significance: Understanding the mechanism of activation of Pyk2 enhances our understanding of the platelet inside-out and outside-in signaling events.

SUMMARY

Proline-rich tyrosine kinase 2 (Pyk2) is activated by various agonists in platelets. We evaluated the signaling mechanism and the functional role of Pyk2 in platelets by using pharmacological inhibitors and Pyk2-deficient platelets. We found that platelet aggregation and secretion in response to 2-MeSADP and AYPGKF were diminished in the presence of Pyk2 inhibitors or in Pyk2-deficient platelets, suggesting that Pyk2 plays a positive regulatory role in platelet functional responses. It has been shown that ADP-, but not thrombin-, induced thromboxane (TxA_{2}) generation depends on integrin signaling. Unlike ADP, thrombin activates G_{12/13} pathways, and G_{12/13} pathways can substitute for integrin signaling for TxA_{2} generation. We found that Pyk2 was activated downstream of both G_{12/13} and integrin-mediated pathways, and both 2-MeSADP- and AYPGKF-induced TxA_{2} generation was significantly diminished in Pyk2-deficient platelets. In addition, TxA_{2} generation induced by co-stimulation of G_{i} and G_{z} pathways, which is dependent on integrin signaling, was inhibited by blocking Pyk2. Furthermore, inhibition of 2-MeSADP-induced TxA_{2} generation by fibrinogen receptor antagonist was not rescued by co-stimulation of G_{12/13} pathways in the presence of Pyk2 inhibitor. We conclude that Pyk2 is a common signaling effector downstream of both G_{12/13} and integrin αIIbβ3 signaling which contributes to thromboxane generation.

Platelet activation plays an important role in hemostasis and thrombosis (1). When platelets are stimulated with agonists, platelets change their shape, aggregate, release their granule contents, generate thromboxane A_{2} (TxA_{2}), leading to the activation of platelets. ADP induces platelet activation by signaling through G_{q}-coupled P2Y_{1} and G_{i}-coupled P2Y_{12} receptors. Unlike ADP, a number of receptors can couple to G_{12/13} including thrombin and TxA_{2}, and platelet shape change induced by these agonists is mediated by both calcium-dependent and –independent mechanisms which occurs through G_{q} and G_{12/13} pathways, respectively (2). G_{12/13} has been shown to regulate Rho-dependent response (3), and RhoA-p160^{ROCK} pathway plays an important role in G_{12/13}-mediated platelet shape change (4). It has also been shown that G_{12/13} pathways regulate dense granule secretion through RhoA-p160^{ROCK} pathways (5) and contribute to the tyrosine phosphorylation of PKCd on Y-311 residue (6) that regulates thromboxane generation (7). Recent studies have shown that G_{12/13} pathways could be activated directly through integrin outside-in signaling events (8).
The non-receptor, proline-rich protein tyrosine kinase Pyk2 is a member of focal adhesion protein tyrosine kinase (FAK) family. Both Pyk2 and FAK have a molecular mass between 110-125 kDa and are closely related in their overall structure. These two kinases lack SH2 and SH3 domains but, in their C-terminal region, possess two proline-rich domains (9). Pyk2 contains an N-terminal FERM domain, a central kinase domain, three proline-rich motifs, and a C-terminal focal adhesion targeting (FAT) domain. Tyr-402 phosphorylation serves as a binding site for Src with subsequent phosphorylation of activation loop residues Tyr-579 and Tyr-580 and Tyr-881 in the FAT domain which promotes binding of the adapter protein Grb2 (10). Recently, Pyk2-knockout mice have been generated and the role of Pyk2 in macrophages (11) and osteoclasts (12) have been studied.

Pyk2 is abundantly expressed in both megakaryocytes and platelets, in addition to brain tissues and epithelial cells (13, 14). Treatment of platelets with several agonists induced the tyrosine phosphorylation of Pyk2 through integrin-dependent and integrin-independent mechanisms (15). They have also shown that Pyk2 tyrosine phosphorylation is regulated by calcium and is mediated through PKC pathways. However, it has been also reported that PKC activation, but not calcium mobilization, is involved in Pyk2 phosphorylation in thrombin-activated platelets (16). Stimulation of human platelets with von Willebrand factor (vWF) also induces the rapid phosphorylation of Pyk2, which is not affected by either calcium chelation or PKC inhibition (17). In addition, Pyk2 phosphorylation has been shown to be mostly dependent on integrin αIIbβ3 and PKC in human platelets (18). Moreover, PI3 kinase activity has been shown to be involved in Pyk2 tyrosine phosphorylation in low-dose thrombin-stimulated platelets (19). In contrast, it has been shown that the Pyk2 activity is not affected by blocking PI3 kinase (20). Thus, the signaling mechanism of Pyk2 activation in platelets is complex and controversial and the functional role of Pyk2 in platelet activation has not been fully understood.

The generation of thromboxane A2 (TXA2), a potent vasoconstrictor and platelet aggregator, is a crucial step in the establishment of a hemostatic plug. Previous study has shown that ADP-induced TXA2 generation depends on outside-in signaling (21). Interestingly, it has been shown that PAR-mediated TXA2 generation occurs independently of integrin αIIbβ3-mediated outside-in signaling, and G12/13 pathways can rescue the inhibitory effect of fibrinogen receptor antagonist to induce TXA2 generation (21). These studies have raised the possibility that G12/13 pathways substitute for integrin-mediated signaling by activating similar effector molecule, but the common signaling molecule downstream of integrins and G12/13 pathways responsible for this event has not been identified.

In the present study, we demonstrate that Pyk2 is activated downstream of both G12/13 and integrin pathways, and both 2-MeSADP- and AYPGKF-induced TXA2 generation is inhibited in Pyk2-deficient platelets. We show that G12/13 pathways fail to substitute for the integrin-mediated outside-in signaling for TXA2 generation when Pyk2 is blocked. Moreover, integrin-dependent TXA2 generation induced by combined Gi and Gz stimulation is abolished by blocking Pyk2. Therefore, we conclude that Pyk2 is a common signaling effector downstream of both G12/13 and integrin αIIbβ3 signaling pathways which plays a crucial role in thromboxane generation in platelets.

Experimental Procedures

Materials—2-MeSADP, acetylsalicylic acid, apyrase (type VII), epinephrine, MRS-2179, sodium citrate, and bovine serum albumin (fraction V) were purchased from Sigma. YFLLRNP and AYPGKF were custom synthesized by Invitrogen. Anti-phospho-Pyk2 (Tyr402), Anti-phospho-Akt (Ser473), anti-phospho-Src (Tyr416), and anti-β Actin antibodies were purchased from Cell Signaling Technology. Anti-phospho-Pyk2 (Tyr881) antibody was from Life Technologies (Grand Island, NY). Horse Radish Peroxidase (HRP)-labeled secondary antibody was from Santa Cruz Biotechnology. 3,5-di-r-Butyl-4-hydroxy-benzylidenemalononitrile (AG17) was from EMD Millipore. SC57101 was a gift from Searle Research and Development (Skokie, IL). TAT-Pyk2-CT and TAT-GFP control were from Xiangdong Zhu, University of Chicago. YM254890 was a gift from Yamanouchi Pharmaceutical (Ibaraki, Japan). All other reagents...
were reagent grade, and deionized water was used throughout.

Animals—Pyk2-deficient mice were obtained from Mitsuhiko Okigaki (Kyoto Prefectural University of Medicine, Kyoto, Japan).

Preparation of human and mouse platelets—Human blood was obtained from a pool of healthy volunteers in a one-sixth volume of acid-citrate-dextrose. Platelet-rich plasma (PRP) was prepared by centrifugation at 230 \( \times g \) for 20 min at room temperature (RT). Acetylsalicylic acid was added to PRP to a final concentration of 1 mM, and the preparation was incubated for 45 min at 37 °C followed by centrifugation at 980 \( \times g \) for 10 min at RT. In the experiments with TxB \(_2\) measurements, the treatment of PRP with acetylsalicylic acid was omitted.

Mouse blood was collected from anesthetized mice into syringes containing 1/10\(^{th}\) blood volume of 3.8% sodium citrate as anticoagulant. Red blood cells were removed by centrifugation at 100 \( \times g \) for 10 minutes at RT. PRP was recovered, and platelets were pelleted at 400 \( \times g \) for 10 minutes. The platelet pellet was resuspended in Tyrode’s buffer (pH 7.4) containing 0.05 units/ml apyrase to a density of 2 \( \times 10^8 \) cells/ml.

Platelet aggregation and secretion—Platelet aggregation was measured using a lumiaaggregometer (Chrono-Log, Havertown, PA) at 37 °C under stirring conditions. A 0.5 ml sample of washed platelets was stimulated with different agonists, and change in light transmission was measured.

Platelet secretion was determined by measuring the release of adenosine triphosphate (ATP) by adding luciferin-luciferase reagent. Platelet ATP release and aggregation were performed in a lumiaaggregometer at 37°C simultaneously.

Western blotting—Platelets were stimulated with agonists for the appropriate time, and phosphorylation events were measured as previously described (22). For outside-in signaling, washed human platelets were plated on fibrinogen-coated cover slips for 45 min at 37°C in a CO\(_2\) incubator, and adherent cells were harvested for immunoblot analysis as described previously (23). In some experiments, platelets were stimulated in the presence of SC57101 (10 \( \mu M \)) to eliminate outside-in signaling.

Measurement of thromboxane A\(_2\) generation—Washed platelets without aspirin-treatment were prepared at a concentration of 2 \( \times 10^8 \) platelets/ml. Stimulations were performed for 3.5 min and the reaction was stopped by snap freezing. Levels of TxB \(_2\) were determined in duplicate using a Correlate-EIA thromboxane B\(_2\) enzyme immunoassay kit (Assay Designs, Inc, Ann Arbor, Michigan), according to the manufacturer’s instructions.

Statistical Analysis—All statistical tests were carried out using Prism software (Version 3.0). Data are presented as means ± S.E. Statistical significance was determined by Student’s t-test and ANOVA. P < .05 was considered statistically significant.

RESULTS

Time- and concentration-dependent phosphorylation of Pyk2 in platelets—It has been shown that treatment of platelets with various agonists including thrombin induces phosphorylation of Pyk2 in platelets. To determine the kinetics of Pyk2 phosphorylation, Tyr\(^{402}\) and Tyr\(^{881}\) phosphorylation in response to PAR4-activating peptide AYPGKF were monitored over a time range of 0.5–2 min. Figure 1A shows a time-dependent increase in Pyk2 phosphorylation in which a rapid increase in Pyk2 phosphorylation in response to AYPGKF was detectable as early as 30 sec after stimulation. We also exposed platelets to different concentrations of AYPGKF, and Tyr\(^{402}\) phosphorylation was measured at 2 min after the addition of agonist. Figure 1B shows a concentration-dependent increase in Pyk2 phosphorylation. An increase in Tyr\(^{402}\) phosphorylation was detectable at concentrations above 100 \( \mu M \) AYPGKF, and higher concentrations induced further phosphorylation that peaked at concentrations above 500 \( \mu M \) AYPGKF. A similar pattern of time- and concentration-dependent phosphorylation of Tyr\(^{402}\) in response to 2-MeSADP, SFLLRN, and thrombin was also detected (data not shown).

Characterization of the activation of Pyk2 downstream of G\(_{12/13}\) and integrin \( \alpha I b \beta 3 \)-dependent outside-in pathways in platelets—Previous studies have shown that Pyk2 is regulated by various cell-type dependent
mechanisms. To investigate the signaling mechanism of Pyk2 activation in platelets, we first evaluated the role of integrin αIIbβ3 in Pyk2 activation. As shown in Figure 2A, Pyk2 was phosphorylated downstream of ADP receptors, which was completely blocked by a fibrinogen receptor antagonist SC-57101. Similarly, 2-MeSADP failed to induce Pyk2 phosphorylation under non-stirring conditions (data not shown). ADP stimulates both Gq and Gi pathways to induce fibrinogen receptor activation. Thus, these results suggest that Pyk2 phosphorylation by ADP occurs in an integrin-dependent manner, and either Gq or Gi pathways cannot directly activate Pyk2. Interestingly, AYPGKF-induced Pyk2 phosphorylation was significantly but not completely inhibited in the presence of SC-57101 (Figure 2B), indicating that AYPGKF-induced Pyk2 phosphorylation occurs through both integrin-dependent and -independent pathways. Unlike ADP, it has been shown that PAR agonists can stimulate G12/13 pathways. Thus, it has raised the possibility that G12/13 pathways can induce Pyk2 phosphorylation in the presence of SC57101 through the integrin-independent pathways.

In order to confirm the contribution of G12/13 and integrin αIIbβ3-mediated outside-in signaling to Pyk2 phosphorylation, we have investigated whether selective activation of G12/13 pathways and integrin αIIbβ3-mediated outside-in signaling can activate Pyk2. We have previously shown that YM-254890 selectively inhibits Gq signaling in platelets, in which AYPGKF caused G12/13-mediated platelet shape change in the presence of YM-254890 that was further abolished by the addition of Rho kinase inhibitor Y-27632 (22). Selective activation of G12/13 pathways by AYPGKF in the presence of Gq selective inhibitor YM254890 resulted in Pyk2 phosphorylation (Figure 3A). It appears that G12/13-mediated Pyk2 phosphorylation plateaus faster than the absence of integrin-mediated signaling because Pyk2 phosphorylation at later time points is mainly mediated by integrin-mediated signaling. Akt phosphorylation was measured to verify the selective activation of G12/13 pathways because we have shown that G12/13 pathways alone cannot induce Akt phosphorylation (22). Selective activation of Gq pathways (2-MeSADP+AR-C69931MX) or Gi pathways (2-MeSADP+MRS2179) failed to induce Pyk2 phosphorylation (Figures 3B and 3C), confirming that Gq and Gi alone cannot cause Pyk2 activation. We have measured Akt phosphorylation to verify the selective blockade of Gq, Gi, or integrin pathways because we and others have shown that ADP-induced Akt phosphorylation is only dependent on Gq pathways (24, 25). In addition, platelet adhesion to immobilized fibrinogen resulted in an increase in the phosphorylation of Pyk2 (Figure 3D), confirming the role of integrin αIIbβ3-mediated signaling in Pyk2 phosphorylation. Platelet adhesion to fibrinogen also caused an increase in the phosphorylation of Src Tyr416, which has been identified as a prominent signaling complex downstream of integrin αIIbβ3 (23). Thus, these results confirm that Pyk2 is activated by both G12/13 pathways and integrin αIIbβ3-mediated outside-in signaling in platelets.

Effect of Pyk2 inhibition on human platelet aggregation and secretion—In order to determine the functional role of Pyk2 in platelets, we first examined the effect of Pyk2 selective inhibitor AG17 on 2-MeSADP-induced aggregation and dense granule secretion. As shown in Figure 4A, 2-MeSADP-induced secondary aggregation and dense granule secretion in washed non-aspirin-treated human platelets were inhibited in the presence of AG17. Thromboxane production in response to ADP in non-aspirin-treated platelets results in dense granule secretion and subsequent secondary aggregation. Thus, it raised the possibility that Pyk2 plays a role in ADP-induced platelet responses through the regulation of TxA2 generation. In order to rule out the secondary effects of TxA2 on 2-MeSADP-induced aggregation, we evaluated the effect of AG17 on aspirin-treated platelets. There was no significant difference in 2-MeSADP-induced platelet aggregation in the presence and absence of AG17 (Figure 4B), indicating the role of Pyk2 in regulating TxA2 generation.

We also observed that platelet aggregation and dense granule release induced by AYPGKF were inhibited in the presence of Pyk2 inhibitor AG17 (Figure 4C). A highly selective TAT-mediated protein transduction of dominant-negative C-terminal Pyk2 (TAT-Pyk2-CT), a fusion protein in which TAT peptide was fused to the C-terminal Pyk2 (amino acid residues 680-1009), has been recently developed to block the activation of Pyk2
(26). Consistent with the result in Fig. 4C, AYPGKF-induced platelet aggregation and secretion were inhibited in the presence of TAT-Pyk2-CT while TAT-GFP control had no effect (Figure 4D). We also compared the effect of Pyk2 inhibition and aspirin treatment in response to AYPGKF, and aspirin treatment had similar inhibitory effect on AYPGKF-induced platelet aggregation and secretion compared to AG17, confirming that Pyk2 inhibits platelet aggregation through the regulation of TxA2 generation. These agonist-induced platelet aggregation and secretion were diminished upon blockade of Pyk2 over a wide range of agonist concentrations. Platelet response was more significantly diminished at lower concentrations of agonist, and differences became minor at higher doses of agonist. These results show that inhibition of Pyk2 in platelets was found to be defective in their function ex vivo, strongly indicating that Pyk2 plays an important role in regulation of platelet function.

Role of Pyk2 in AYPGKF-induced platelet aggregation, secretion, and TxA2 generation in Pyk2-deficient platelets—As pharmacological inhibitors are known to have off-target and broad-spectrum effects, we have examined platelets from Pyk2 +/- mice to ascertain the role of Pyk2 in platelet function. Consistent with the results obtained with Pyk2 inhibitors, platelet aggregation (Figure 5A) and ATP secretion (Figure 5B) were diminished in Pyk2-deficient platelets compared to the wild type platelets. In addition, Pyk2 inhibitor AG17 did not show additional inhibitory effect on AYPGKF-induced platelet aggregation in Pyk2-deficient platelets, indicating that the effects of AG17 are likely mediated by Pyk2. Similarly, the concentration response curves for AYPGKF-induced TxA2 generation were shifted to the right in Pyk2-deficient platelets as the level of TxB2 generation in Pyk2-deficient platelets in response to AYPGKF was significantly decreased compared to WT platelets (Figure 5C), suggesting that Pyk2 positively regulates TxA2 generation. Because TxA2 has a short half-life and is rapidly converted to stable product TxB2, TxB2 was measured as TxA2 by ELISA. It has been shown that PAR agonists cause TxA2 generation independently of integrin signaling, and we have observed that Pyk2 is activated by both G12/13 pathways and integrin signaling (Figure 3). Thus, our results have raised the possibility that Pyk2 is the common signaling molecule downstream of both G12/13 pathways and integrin signaling which plays an essential role in AYPGKF-induced TxA2 generation.

Role of Pyk2 in 2-MeSADP-induced secretion and TxA2 generation in Pyk2-deficient platelets—It has been shown that ADP-induced TxA2 generation and subsequent secretion is dependent on integrin activation. In order to confirm the role of Pyk2 downstream of integrins, we next measured TxA2 generation and ATP secretion in response to 2-MeSADP in Pyk2-deficient platelets. Consistent with the result in Fig. 4A, 2-MeSADP-induced ATP secretion (Figure 6A) and TxA2 generation (Figure 6B) were completely inhibited in Pyk2-deficient platelets, confirming the contribution of Pyk2 to TxA2 generation downstream of integrins.

Effect of Pyk2 on regulation of TxA2 generation downstream of integrin-dependent outside-in and G12/13 pathways—We have previously shown that combined stimulation of G1 and G2 pathways causes platelet aggregation and thromboxane generation which is dependent on integrin-mediated outside-in signaling (27). In order to verify the role of Pyk2 in outside-in signaling, we first tested the effect of Pyk2 inhibition on platelet aggregation under these conditions. As shown in Figure 7A, combination of G1 stimulation (2-MeSADP plus P2Y1 antagonist MRS2179) with G2 pathways (epinephrine) caused robust aggregation and dense granule secretion in non-aspirin-treated human platelets. However, pretreating the platelets with AG17 caused an inhibition in secondary platelet aggregation and dense granule secretion. Since secondary platelet aggregation and dense granule secretion in this condition is mediated by TxA2 generation which is dependent on outside-in signaling, we then measured the effect of Pyk2 inhibition on TxA2 generation induced by co-stimulation of G1 and G2 pathways. Selective stimulation of G1 (2-MeSADP plus MRS2179) or G2 pathways (epinephrine) alone failed to cause TxA2 generation (Figure 7B). However, co-stimulation of G1 and G2 pathways caused a significant increase in TxA2 generation as previously described (27). When platelets were pre-treated with SC57101 or AG17, co-stimulation of G1 and G2 pathways failed to induce TxA2 generation, indicating that Pyk2 is necessary for
thromboxane generation mediated by outside-in signaling.

The study from our group has also shown that inhibition of ADP-induced thromboxane generation by fibrinogen receptor antagonist was rescued by co-stimulation of G\textsubscript{12/13} pathways by YFLLRNP (21), suggesting that G\textsubscript{12/13} pathways can substitute integrin-mediated signaling by probably activating common signaling effector downstream of both integrins and G\textsubscript{12/13} pathways. To confirm the role of Pyk2 downstream of G\textsubscript{12/13} pathways in Tx\textsubscript{A2} generation, we co-stimulated platelets with 2-MeSADP and YFLLRNP in the presence of fibrinogen receptor antagonist SC57101 and then compared the effect of Pyk2 inhibitor AG17 on Tx\textsubscript{A2} generation. As shown in Figure 7C, 2-MeSADP-induced Tx\textsubscript{A2} generation was completely blocked in the presence of SC57101 or AG17, confirming the role of Pyk2 in ADP-induced Tx\textsubscript{A2} generation which depends on integrin-mediated signaling. Selective activation of G\textsubscript{12/13} pathways with YFLLRNP failed to cause Tx\textsubscript{A2} generation, but co-stimulation of platelets with 2-MeSADP and YFLLRNP in the presence of SC57101 caused significant increase in Tx\textsubscript{A2} generation, indicating that G\textsubscript{12/13} pathways substitute for integrin signaling for Tx\textsubscript{A2} generation. However, Tx\textsubscript{A2} generation under these conditions was completely blocked by AG17, confirming that G\textsubscript{12/13} pathways rescue integrin-mediated outside-in signaling for Tx\textsubscript{A2} generation through Pyk2.

**DISCUSSION**

It has been shown that Pyk2 is abundantly expressed in platelets and is activated by various agonists including thrombin, collagen or vWF in platelets (15). However, the signaling mechanism of Pyk2 activation in platelets is complex and controversial and the functional role of Pyk2 in platelet activation has not been fully understood. Therefore, we have used pharmacological inhibitors of Pyk2 and Pyk2-deficient platelets to identify the signaling pathways of Pyk2 and its role in platelet function.

Pyk2 has been shown to be phosphorylated through integrin-mediated pathways, intracellular Ca\textsuperscript{2+} mobilization, and protein kinase C (PKC) activation in several cells, including human B cells (28), neurons (29), CMK megakaryocytic cells (30, 31), and PC12 cells (14, 32). However, it has been shown that Pyk2 activation mediated by thrombin is dependent on intracellular calcium but not dependent on PKC, Src, or PI3-kinase in human endothelium (33). It has also been shown that several platelet agonists induce the tyrosine phosphorylation of Pyk2 through integrin-dependent and integrin-independent mechanism (15). Thus, there appears to be cell-type dependent mechanism regulating Pyk2 activation. We have investigated whether selective activation of G\textsubscript{12/13} pathways, G\textsubscript{4} pathways, G\textsubscript{1} pathways, and integrin-mediated outside-in signaling can activate Pyk2. We found that 2-MeSADP-induced Pyk2 phosphorylation was induced by integrin-dependent pathways whereas PAR agonists-induced Pyk2 phosphorylation was dependent on both integrin-dependent and –independent mechanism in platelets. PAR agonists can couple to G\textsubscript{12/13} pathways, and we observed that selective activation of G\textsubscript{12/13} pathways resulted in Pyk2 phosphorylation. We also observed that 2-MeSADP failed to induce Pyk2 phosphorylation in the presence of P2Y\textsubscript{1} or P2Y\textsubscript{12} receptor antagonists indicating that G\textsubscript{q} or G\textsubscript{i} pathways alone cannot directly activate Pyk2. Thus it appears that some of inhibitory effect of other signaling molecules on Pyk2 activation in the previous studies might not be due to their direct inhibitory effect on Pyk2 but might be related to their inhibitory effect on platelet aggregation and the subsequent outside-in signaling.

Only few selective inhibitors of Pyk2 have been identified. As pharmacological inhibitors are known to have off-target and broad-spectrum effects, the effect of Pyk2 in platelets has not been completely determined. Salicylate has been shown to inhibit Pyk2 phosphorylation, but it also exhibits an inhibitory effect on c-Src (34). It has recently been shown that Pyk2 inhibitor AG17 reduces neutrophil adhesion to adherent platelets (35). A highly selective TAT-mediated protein transduction of dominant-negative C-terminal Pyk2 (TAT-Pyk2-CT) has been recently developed and used in several studies to selectively inhibit Pyk2 activity (26, 36-38). We have demonstrated the efficacy of these inhibitors on Pyk2 phosphorylation induced by AYPGKF in Supplemental Figure 1. Importantly, Pyk2-knockout mice have been generated and the role of Pyk2 in macrophages (11) and osteoclasts (12).
have been studied. We found that platelet aggregation and dense granule release induced by various agonists including 2-MeSADP and AYPGKGF were inhibited in the presence of Pyk2 inhibitors AG-17 and TAT-Pyk2-CT in human platelets suggesting that Pyk2 positively regulates platelet function. Consistently, platelet aggregation and secretion induced by 2-MeSADP and AYPGKGF were diminished in Pyk2-deficient platelets compared to WT platelets.

It has been shown that ADP-induced TxA2 generation requires outside-in signaling whereas thrombin-mediated TxA2 generation occurs independently of outside-in signaling. Platelets from patients with Glanzmann’s thrombasthenia or platelets treated with fibrinogen receptor antagonist have been shown to be defective in ADP-, but not thrombin-, induced TxA2 generation and secretion (39, 40). Unlike ADP, thrombin can couple to G12/13 pathways, and previous study has shown that inhibition of ADP-induced TxA2 generation by integrin αIIbβ3 blockade is rescued by co-stimulation of G12/13 pathways (21). These studies suggest that thrombin substitutes outside-in signaling through G12/13 pathways thus enables to generate thromboxane in the absence of outside-in signaling. These observations also suggest the existence of a common signaling effector downstream of both integrins and G12/13 pathways. If Pyk2 is the common effector molecule downstream of both integrins and G12/13 pathways contributing to thromboxane generation, we anticipated that integrin-mediated TxA2 generation by 2-MeSADP and G12/13-dependent TxA2 generation by AYPGKGF would be inhibited upon inhibition of Pyk2. Interestingly, we found that 2-MeSADP- and AYPGKGF-induced TxA2 generation was inhibited in Pyk2 -/- platelets compared to WT platelets. Our data showed that the extent of inhibition of platelet aggregation caused by Pyk2 inhibition was similar to the one caused by aspirin treatment, confirming the role of Pyk2 in TxA2 generation. In addition, we found that Pyk2 inhibition had no effect on ADP-induced platelet aggregation in aspirin-treated platelets, which is consistent with previous study showing that there was no difference in ADP-induced platelet aggregation from WT or TxA2 receptor null mice (41). Recent study has characterized the platelets from Pyk2 knockout mice and no significant differences are observed between WT and Pyk2 knockout mice (42). In addition, arachidonic acid induces normal platelet aggregation in Pyk2-deficient platelets, and Pyk2 is linked to cPLA2 activation (42). In the experimental model adopted from previous study (21) to confirm the role of Pyk2 downstream of G12/13 pathways in TxA2 generation, we found that G12/13 pathways failed to substitute for integrin-mediated signaling for TxA2 generation in the presence of Pyk2 inhibitor confirming the contribution of Pyk2 downstream of G12/13 pathways. In addition, we have previously shown that combined P2Y12 receptor and α2A adrenergic receptor stimulation causes TxA2 generation with a requirement for outside-in signaling through αIIbβ3 (27). Our data showed that Pyk2 inhibitor and αIIbβ3 antagonist completely inhibited TxA2 generation caused by costimulation of Gi and Gz signaling, further confirming an essential role of Pyk2 in TxA2 generation that is activated by outside-in signaling. Combined with our results showing that Pyk2 is activated downstream of both G12/13 and integrin-mediated outside-in pathways, these results strongly suggest that Pyk2 is the common effector molecule downstream of both G12/13 and outside-in signaling pathways which contribute to TxA2 generation in platelets.

Recently, it has been shown that Pyk2 is activated after integrin α2β1 engagement in platelets and that Pyk2 regulates PI 3-kinase β activity after integrin α2β1-mediated adhesion (43). PI 3-kinase β has been shown to play an important role in signaling downstream of αIIbβ3 (44), and our work has shown that PI 3-kinase β plays an important role in ADP-induced TxA2 generation (45). Thus, it is possible that Pyk2 mediates ADP-induced TxA2 generation by regulating PI 3-kinase β activity in platelets.

We have previously shown that ADP-induced TxA2 generation requires both P2Y1- and P2Y12-mediated signaling (46). However, the present study showed that selective activation of either P2Y1 or P2Y12 signaling failed to induce Pyk2 activation and identified an important role of Pyk2 downstream of integrins in ADP-induced TxA2 generation that is dependent on outside-in signaling. ADP fails to induce platelet aggregation when either P2Y1 or P2Y12 receptor is blocked (47). Thus this suggests that the inhibitory effect
of either P2Y₁ or P2Y₁₂ on ADP-induced TxA₂ generation might be due to their inhibitory effect on platelet aggregation which leads to the blockade of integrin-mediated signaling and Pyk2 activation.

Pyk2 is highly homologous to FAK which plays a key role in mediating signaling downstream of integrins (48). Expression level of FAK in Pyk2 knockout platelets has been shown to be normal. Previous study has shown that FAK is activated downstream of integrins and G₁₂/₁₃ pathways in platelets, and 2-MeSADP-induced TxA₂ generation is inhibited in the presence of FAK inhibitor TAE-226 (21). However, 2-MeSADP-induced TxA₂ generation was not affected in Pf4-Cre/FAK-floxed mice indicating that FAK does not contribute to TxA₂ generation induced by outside-in signaling. Since TAE-226 also inhibits Pyk2 at higher concentration (10), the inhibitory effect of TAE-226 on TxA₂ generation was probably through the inhibition of Pyk2 which is consistent with our results using Pyk2 inhibitors.

In conclusion, we have demonstrated that Pyk2 is an important functional tyrosine kinase that is activated by both G₁₂/₁₃ and integrin αIIbβ₃-mediated outside-in signaling pathways and plays an important role in regulation of TxA₂ generation in platelets.

REFERENCES


**FOOTNOTES**

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The abbreviations used are: Pyk2, proline-rich tyrosine kinase 2; TxA2, thromboxane A2; PAR, protease activated receptor; 2-MeSADP, 2-methylthio-ADP; AG17, 3,5-di-t-Butyl-4-hydroxybenzylidenemalononitrile; PRP, platelet-rich plasma

**FIGURE LEGENDS**

**FIGURE 1.** Time- and Dose-dependent phosphorylation of Pyk2 in response to AYPGKF.

(A) Washed human platelets were stimulated at 37 °C for the time points indicated with AYPGKF (500 µM). (B) Washed platelets were stimulated with different concentrations of AYPGKF for 2 min at 37 °C. The reaction was stopped by the addition of 3X SDS sample buffer. Samples were separated by SDS-PAGE, transferred onto polyvinylidene difluoride membranes, and probed with anti-phospho-Pyk2 (Tyr⁴⁰² or Tyr⁸⁸¹), anti-Pyk2, or anti-β-actin (lane loading controls) antibodies. The data shown are representative of three experiments.

**FIGURE 2.** The effect of integrin αIIbβ3 inhibition on Pyk2 phosphorylation induced by 2-MeSADP and AYPGKF. Platelets were stimulated with 100 nM 2-MeSADP (A) or 500 µM AYPGKF (B) at 37 °C for 2 min in the presence and absence of 10 µM SC57101. Equal amounts of proteins were separated by SDS-PAGE, Western-blotted, and probed for anti-phospho-Pyk2 (Tyr⁴⁰²) or anti-β-actin (lane loading control) antibodies. The blot shown is a representative of three independent experiments. (C and D) Densitometric measurement of phospho-Pyk2, expressed as fold increase over control. Data are mean ± S.E. (n = 3). *P < .05.

**FIGURE 3.** Activation of Pyk2 downstream of G12/13 and outside-in signaling. (A) Washed human platelets were stimulated in the presence of 100 nM YM254890 with 500 µM AYPGKF for various time points and probed with anti-phospho-Pyk2 (Tyr⁴⁰² and Tyr⁸⁸¹), anti-phospho-Akt (Ser⁴⁷³), or anti-β-actin (lane loading control) antibodies by western blotting. (B) Platelets were stimulated with 100 nM 2-MeSADP for 2 min in the presence and absence of 100 µM MRS2179, 100nM AR-C69931MX, or 10 µM SC57101 and probed with anti-phospho-Pyk2 (Tyr⁴⁰²), anti-phospho-Akt (Ser⁴⁷³), or anti-β-actin (lane loading control) antibodies by western blotting. (C) Densitometric measurement of phospho-Pyk2 and phospho-Akt, expressed as fold increase over control. Data are mean ± S.E. (n = 3). *P < .005 compared to agonist. (D) Lysates from non-adherent (BSA) and fibrinogen-adherent (Fib) platelets were probed with anti-phospho-Pyk2 (Tyr⁴⁰² and Tyr⁸⁸¹), anti-phospho-Src (Tyr⁴¹⁸), or anti-β-actin (lane loading control) antibodies. The blot shown is a representative of three independent experiments.
FIGURE 4. The effect of Pyk2 inhibition on agonist-induced platelet aggregation and secretion. (A) Non-aspirin-treated and (B) aspirin-treated washed human platelets were pre-treated with Pyk2 inhibitor AG17 (1 μM) at 37 °C for 5 min following stimulation with 50 nM 2-MeSADP under stirring conditions. Non-aspirin-treated and aspirin-treated (ASA) washed human platelets were pre-incubated with Pyk2 inhibitors (C) AG17 (1 μM) or (D) TAT-Pyk2-CT (2 μM) or TAT-GFP (control) at 37 °C for 3.5 min and stimulated with 60 μM AYPGKF. Platelet aggregation and ATP secretion were measured by aggregometry. Arrow indicates when agonist is added. Tracings are representative of experiments performed using platelets from at least three different donors.

FIGURE 5. AYPGKF-induced platelet aggregation, secretion, and TxA2 generation in Pyk2-deficient platelets. Non-aspirin-treated washed platelets from Pyk2−/− mice and Pyk2+/+ litters were stimulated with different concentrations of AYPGKF at 37 °C for 3.5 min, and (A) platelet aggregation, (B) ATP secretion, and (C) TxA2 generation were measured as described in “Materials and methods”. Arrow indicates when agonist is added. In some experiments, platelets were pre-incubated with 1 μM AG17 prior to platelet stimulation as noted. All data shown are representative of three independent experiments. Data are mean ± S.E. (n = 3). *P < .05; **P < .005 compared to wild-type.

FIGURE 6. 2-MeSADP-induced secretion and TxA2 generation in Pyk2-deficient platelets. Non-aspirin-treated washed platelets from Pyk2−/− mice and Pyk2+/+ litters were stimulated with 100 nM 2-MeSADP for 3.5 min, and (A) ATP secretion and (B) TxA2 generation were measured. The values are representative of three independent experiments. Data are mean ± S.E. (n = 3). *P < .005.

FIGURE 7. Effect of Pyk2 to TxA2 generation downstream of integrins and G12/13 pathways. (A) Non-aspirin-treated washed human platelets were pre-treated with AG17 (1 μM) at 37 °C for 5 min following co-stimulation with 100 nM 2-MeSADP and 10 μM epinephrine in the presence of 100 μM MRS2179 for 3.5 min under stirring conditions. Platelet aggregation and ATP secretion were measured by aggregometry. Arrow indicates when agonist is added. Tracings are representative of three independent experiments. (B) The effect of Pyk2 inhibition on combined Gι and Gz stimulation on TxA2 generation. 10 μM SC57101 was added 1 min prior to the addition of agonists where noted. (C) The effect of Pyk2 inhibition on G12/13-dependent TxA2 generation. Non-aspirin-treated washed human platelets were stimulated with either 100 nM 2-MeSADP, 60 μM YFLLRNP, or 100 nM 2-MeSADP + 60 μM YFLLRNP as indicated for 3.5 min, and the effect of AG17 on TxA2 generation was measured. Data are mean ± S.E. (n = 3). *P < .005.
Figure 1

A

P-Pyk2 (Tyr402)
P-Pyk2 (Tyr881)
Total
Pyk2
β-Actin

Time (Sec) 0 15 30 60 120 180

B

P-Pyk2 (Tyr402)
β-Actin

AYPGKF Dose (μM) 0 100 200 500 1000
Figure 2
Figure 3
Figure 4
Figure 4
Figure 5
Figure 6
Figure 7
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Figure 7
Distinct role of PYK2 in mediating thromboxane generation downstream of both G12/13 and integrin αiibβ3 in platelets
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