Platelet Secretion and Hemostasis Require Syntaxin-binding Protein STXBP5

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Platelet secretion and hemostasis require syntaxin-binding protein STXBP5

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Genome-wide association studies (GWAS) have linked genes encoding several soluble NSF attachment protein receptor (SNARE) regulators to cardiovascular disease risk factors. Because these regulatory proteins may directly affect platelet secretion, we used SNARE-containing complexes to affinity purify potential regulators from human platelet extracts. Syntaxin-binding protein 5 (STXBP5; also known as tomosyn-1) was identified by mass spectrometry, and its expression in isolated platelets was confirmed by RT-PCR analysis. Coimmunoprecipitation studies showed that STXBP5 interacts with core secretion machinery complexes, such as syntaxin-11/SNAP23 heterodimers, and fractionation studies suggested that STXBP5 also interacts with the platelet cytoskeleton. Platelets from Stxbp5 KO mice had normal expression of other key secretory components; however, stimulation-dependent secretion from each of the 3 granule types was markedly defective. Secretion defects in STXBP5-deficient platelets were confirmed via lumi-aggregometry and FACS analysis for P-selectin and LAMP-1 exposure. Interestingly, STXBP5-deficient platelets had altered granule cargo levels, despite having normal morphology and granule numbers. Consistent with secretion and cargo deficiencies, Stxbp5 KO mice showed dramatic bleeding in the tail transection model and defective hemostasis in the FeCl3-induced carotid injury model. Transplantation experiments indicated that these defects were due to loss of STXBP5 in BM-derived cells. Our data demonstrate that STXBP5 is required for normal arterial hemostasis, due to its contributions to platelet granule cargo packaging and secretion.

Introduction
Cardiovascular diseases, such as myocardial infarction, stroke, and deep vein thrombosis, are leading causes of death and disability. These potentially occlusive processes are influenced in part by platelet secretion (1, 2). As a physiological response to vascular damage, platelets are activated and secrete components that promote thrombus formation and initiate its sequelae, e.g., wound healing and angiogenesis (1, 3, 4). Platelet secretion is mediated by highly conserved soluble N-ethylmaleimide–sensitive factor (NSF) attachment protein receptor (SNARE) proteins: vesicle/granule SNAREs (v-SNAREs) consist of the vesicle-associated membrane proteins (VAMPs), and target membrane SNAREs (t-SNAREs) consist of 2 classes, syntaxins and members of the synaptosomal-associated protein 23/25 (SNAP23/25) family. A trans-membrane complex of these 3 proteins mediates bilayer fusion and thus granule cargo release (5). In human and mouse platelets, this core fusion complex includes VAMP8, SNAP23, and syntaxin-11 (STX11) (6–9). These core elements are acted on by regulatory proteins, which affect when and where SNARE interactions occur. This assures physiologically relevant secretion (10, 11). In platelets, syntaxin regulators such as Munc18b and tethering proteins such as Munc13-4 and Rab27 are required for granule release (1, 12, 13). Genome-wide association studies (GWAS) have linked other regulatory proteins to cardiovascular diseases (14–20); thus, to understand the significance of these associations, it is important to determine which types of SNARE regulators control platelet secretion.

In our continuing effort to identify new secretion regulators, we used t-SNARE–containing complexes to capture SNARE-binding proteins from platelet extracts. We identified syntaxin-binding protein 5 (STXBP5; also known as tomosyn-1 [i.e., “friend of syntaxin”]) as a novel candidate for affecting platelet secretion. STXBP5 is a 130-kDa protein that was originally identified as a STX1-binding partner in neuronal tissue (21). Subsequent studies have shown that STXBP5 interacts with other syntaxin isoforms and is widely expressed (22). STXBP5 belongs to a family of WD40 repeat-containing proteins associated with exocytosis and with the actin cytoskeleton: Sro7/Sro77 in yeast, Tom1 in C. elegans, and STXBP5 in mammals (23–28). In mammals, 2 genes are present, Stxbp5 and Stxbp5l (also known as Tomosyn-2), and alternative splicing produces 7 protein isoforms (29, 30). STXBP5 has 3 isoforms, based on molecular weight: big, middle, and small (b-STXBP5, m-STXBP5, and s-STXBP5, respectively). Structurally, STXBP5 is composed of an N-terminal WD40 repeat (~90% of the total protein sequence), a highly variable linker region, and a C-terminal v-SNARE (or R-SNARE) motif (31). The v-SNARE motif is proposed to exert a negative effect on fusogenic SNARE complex assembly by blocking v-SNARE binding to t-SNAREs (31). Consistently, overexpression of STXBP5 in neurons and neuroendocrine secretory cells inhibits exocytosis, and gene mutations in C. elegans or genetic deple-
tion of Stxbp5 in mice enhances synaptic transmission (24, 32, 33). However, the N-terminal domain of STXBP5, lacking the syntaxin-binding v-SNARE motif, can also inhibit secretion from PC-12 cells, which suggests that other interactions with STXBP5 are important (33). Conversely, knockdown of STXBP5 in superior cervical ganglion neurons (34) and in the rat β cell line INS-1E (35), and genetic depletion of the homologs Sro7 and Sro77 in yeast (25), negatively affects exocytosis. Thus, although STXBP5 may be a negative regulator of secretion in some cells, it may play a positive role in others (24). To date, the role of this potential SNARE regulator in platelets has not been addressed.

Various studies have linked STXBP5 with neuropsychological and cardiovascular diseases in humans. Deletions in the Stxbp5 gene are linked to autism (36). GWAS show genetic variations in Stxbp5 are linked with increased plasma levels of vWF (14–19), alterations in tissue plasminogen activator (tPA) levels (20), venous thrombosis (16), and arterial thrombosis (19). Specifically, 1 SNP that produces a nonsynonymous mutation (N436S) was associated with increased bleeding (18). These associations suggest a role for STXBP5 in both endothelial cell (EC) and platelet secretion and point to a role for the protein in normal hemostasis. In the present study, we examined the platelet phenotype of mice lacking STXBP5 to understand how this t-SNARE regulator affects platelet exocytosis, granule biogenesis, and hemostasis.

Results

**STXBP5 is present in human platelets.** The critical SNAREs in platelets have been identified: STX11 and SNAP23 as the t-SNAREs, and VAMP8 as the primary v-SNARE (6, 8, 9). Of these 3 SNARE types, syntaxins and their binding proteins have dominated the ranks of potential secretion regulators, which suggests that syntaxins or syntaxin-containing complexes might serve as useful “bait” to identify additional secretion regulators. Because of our problems with the insolubility of STX11 when expressed in bacteria (S. Ye and J. Zhang, unpublished observation), STX2 and STX4 were used as surrogates to create syntaxin-SNAP23 and syntaxin-Munc18 complexes for pulldown assays. Using human platelet extracts and various syntaxin-containing complexes as bait, we recovered 5 bands that represented proteins specifically bound to 1 or more of the syntaxin-containing baits used (Figure 1A). Mass spectrometry analysis showed that bands T1 and T2 were STXBP5, band T3 was phosphofructokinase C, band T4 was Munc18b, and band T5 was granuphilin (also known as SLP4) (Figure 1 and Supplemental Table 1; supplemental material available online with this article; doi:10.1172/JCI75572DS1). Munc18b is known to be required for platelet secretion and to bind to t-SNARE complexes (13, 37). Granuphilin is a known Rab27 effector and is important for dense granule secretion (12, 38). The role of phosphofructokinase is unclear at present. STXBP5 has been shown to be involved in neuronal and neuroendocrine exocytosis (21, 24, 39). Platelet STXBP5 (bands T1 and T2) was specifically associated with t-SNARE heterodimers, consistent with previous reports showing that STXBP5 forms ternary complexes with STX4/SNAP23 and STX1/SNAP25 (22, 31). To verify STXBP5 expression in human platelets and our mass spectrometry results, we probed platelet extracts and affinity-purified complexes by IB using an anti-STXBP5 peptide mAb (whose epitope is a region shared by all 3 isoforms). A specific immunoreactive band was only seen in samples bound to the t-SNARE heterodimers, not in those bound to Munc18a- or Munc18c-containing complexes (Figure 1B). To determine which STXBP5 isoforms were present in human platelets, RT-PCR analysis was performed using random hexamers and oligo d(T)16 primers, followed by regular PCR using isoform-specific primers for s-STXBP5, m-STXBP5, and b-STXBP5 (see Methods). The 1-kb DNA ladder standard is at the far left.
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Figure 2. STXBP5 is associated with platelet SNARE complexes and cytoskeleton. (A–D) Platelet extracts (Input) from resting (R) or thrombin-stimulated (S) platelets were prepared by solubilization with 1% Triton X-100. After clarification, platelet extracts were incubated with anti-STXBP5 mAb (A) or rabbit polyclonal Ab (B and D), anti-STX11 rabbit polyclonal Ab (C), anti-Munc18b goat polyclonal Ab (D), or IgG control for 3 hours at 4°C. Immune complexes were recovered with protein A and G sepharose. The bound proteins were eluted and separated by SDS-PAGE, followed by IB with the indicated antibodies. (E) Washed platelets (2.5 × 10^8) were resuspended in HEPES/Tyrode buffer and incubated with (stimulated) or without (resting) 0.1 U/ml thrombin for 5 minutes. After disruption by freeze-thaw, the unbroken cells were removed by centrifugation at 700 g for 5 minutes, and supernatants were subjected to ultracentrifugation (100,000 g for 1 hour at 4°C). The cytosolic fractions (S1) were collected. The remaining pellets were solubilized sequentially with Triton X-100 (S2), then n-octyl-β-D-glucopyranoside (S3). The supernatants and insoluble pellet (P) were analyzed by IB with the indicated antibodies. T, total extract (starting material for the fractionation).

STXBP5 is associated with platelet SNARE machinery. To demonstrate that STXBP5 does interact with the functionally relevant syntaxin isoform in platelets, STX11 (as well as SNAP23 and VAMP8), we immunoprecipitated endogenous STXBP5 from detergent-solubilized extracts and probed the precipitate with antibodies against known elements of the platelet secretory machinery. Both resting and thrombin-stimulated human platelets were lysed with Triton X-100, and immunoprecipitation was performed using nonspecific IgG or an anti-STXBP5 mAb. It should be noted that much of the platelets STXBP5 was in the pellet fraction under these conditions; however, we chose to focus only on the soluble pool, so as to lessen the chance of detecting artificial interactions due to incomplete solubilization. IB showed that the t-SNAREs STX11 and SNAP23 were recovered in the STXBP5 immunoprecipitates (Figure 2, A and B). Reciprocal immunoprecipitation with anti-STX11 antibodies confirmed this interaction (Figure 2C). In agreement with the in vitro pulldown results (Figure 1A), endogenous STXBP5 could also bind STX2 and STX4. No VAMP3 or VAMP8 was detected, consistent with the notion that STXBP5 competes with v-SNAREs to bind t-SNARE complexes (31). Another platelet secretory component, Munc18b, was coimmunoprecipitated with STXBP5 (Figure 2B). Reciprocal immunoprecipitation confirmed the STXBP5/Munc18b interaction (Figure 2D). At this stage, it was not mechanistically clear why the complex composition was unaffected by platelet activation. Regardless, these data showed that STXBP5 associated with the critical secretory components SNAP23, STX11, and Munc18b in platelets and that its association was exclusive of the VAMPs.

STXBP5 localization in platelets. We next sought to determine the distribution of STXBP5 in platelets using biochemical fractionation and immunofluorescence microscopy. Resting and thrombin-activated platelets were disrupted by repeated freeze-thaw and separated into cytosolic and pelleted fractions by centrifugation (Figure 2E). The pelleted fractions were extracted sequentially with Triton X-100 and n-octyl-β-d-glucopyranoside to solubilize membrane proteins and lipid raft components, respectively. The cytosolic marker RabGDI fractionated into the first supernatant, and the membrane protein marker STX4 was found in the Triton X-100–solubilized fraction. The raft marker SNAP23 was present both in the Triton X-100–solubilized fraction and in the n-octyl-β-d-glucopyranoside–solubilized fraction. STXBP5 was found in the final cytoskeletal pellet, consistent with actin’s presence (43). The distribution of STXBP5 in platelets (spread on fibrinogen-coated coverslips) was also suggestive of interaction with the cytoskeleton. STXBP5 was concentrated in the central region of the platelets and was surrounded by phalloidin-stained actin filaments (Figure 3, A–D). Because these platelets were surface-activated by spreading on coated glass, few granules remained, but P-selectin staining did appear in the central area of some platelets (Figure 3, A–D), consistent
and subjected to IB analysis. The protein levels of 14 known secretory machinery components were examined; other than STXBP5, none appeared to be significantly altered (Figure 4A). To understand the role of STXBP5, we examined stimulation-dependent release of cargo from all 3 platelet granules: dense granules, α granules, and lysosomes. Secretion of granule cargo from Stxbp5 KO and WT platelets showed the expected thrombin dose dependence (Figure 4B); however, the percentage release from α granules and lysosomes was significantly affected by the loss of STXBP5. The release from dense granules was significantly affected, but to a lesser extent, in this assay system. The kinetics of secretion from

**STXBP5 is important for platelet secretion.** To explore the functional role of STXBP5, we analyzed Stxbp5 KO mice. As might be predicted from GWAS analysis (14–19), plasma vWF levels were increased in these mice, although plasma IgG was unaffected, as indicated by light chain levels (Supplemental Figure 1). Platelet extracts from Stxbp5 KO and littermate WT mice were prepared

![Figure 3. STXBP5 is present in platelets. Washed human platelets were allowed to bind to fibrinogen-coated coverslip for 1 h at 37°C. After washing away the unbound platelets, the bound platelets were fixed and immunostained for STXBP5 (A), P-selectin (B) and F-actin using TRITC-phalloidin (C). Platelets were additionally stained with anti-STXBP5 antibodies (E, I, and M), anti-tubulin antibodies (G, K, and O) and antibodies against markers for α granules (vWF; F), lysosomes (LAMP-1; J), and dense granules (CD63; N). Images in A–D were taken using a Zeiss LSM 780 confocal microscope and processed using ZEN blue software, and images in E–P were taken using a Nikon A1R confocal microscope and processed using NIS-Elements AR 3.2 software; D, H, L, and P show 3-color merged views. Scale bars: 10 μm (A–D); 1 μm (A–D, insets, and E–P).](image-url)
Stxbp5 KO platelets was also significantly defective upon activation with 0.1 U/ml thrombin (Figure 4C).

Because dense granule release is such a rapid process, measuring [3H]-serotonin in our assay configuration at room temperature (Figure 4, B and C) may not be sufficient to fully appreciate a subtle, albeit significant, kinetic defect. To rectify this, we applied more sensitive lumi-aggregometry to analyze ATP/ADP release from dense granules. ATP/ADP release in response to 100 μM PAR-4, 10 nM A23187, 0.1 μg/ml convulxin, and 0.025, 0.05, and 0.1 U/ml thrombin was substantially inhibited, whereas aggregation was not (Figure 5). Quantification of ATP/ADP release from 3 independent experiments showed significant reductions in Stxbp5 KO platelets (Figure 5, D and K). To further confirm that STXBP5 is required for granule and lysosome release, exposure of the respective markers P-selectin and LAMP-1 was analyzed by flow cytometry. Consistently, activation-dependent exposure of both granule membrane markers was reduced approximately 2-fold in Stxbp5 KO versus WT platelets (Figure 6, A and B).

In agreement with the aggregation data, there was no significant difference in PE-conjugated JonA staining (Figure 6C), which suggests that depletion of STXBP5 did not affect integrin αIIbβ3 activation (15, 44, 45). Electron microscopy (EM) analysis detected no overt morphology differences in Stxbp5 KO platelets (Supplemental Figure 2). Upon thrombin stimulation, there was similar filopodia formation in both WT and Stxbp5 KO platelets, which suggests that deficiency of STXBP5 did not affect platelet cytoskeletal rearrangements or platelet activation, but did affect secretion. Additionally, adhesion to fibrinogen was not affected in cytoskeletal rearrangements or platelet activation, but did affect which suggests that deficiency of STXBP5 did not affect platelet section when dense and α granules were counted (Table 1). These data suggest that STXBP5 contributes to granule biogenesis as well as to secretion. To characterize the effect of STXBP5 loss on platelet cargo, we probed extracts with granule-specific antibodies (Figure 7, A and B). IB data confirmed the reduction of PF4 and showed reduced levels of factor V. Platelet fibrinogen and vWF levels were modestly affected. The total levels of granule membrane proteins (e.g., LAMP-1 and P-selectin) were only slightly affected, while the surface expression of several platelet markers (e.g., GP1b, GPVI, and PECAM-1) was largely unaffected (Figure 7, B and C). Consistent with the levels of LAMP-1 and P-selectin, EM analysis showed no significant difference in the number of granules present per platelet section when dense and α granules were counted (Table 1). These data argue that granules are made, but may not be normally loaded with cargo. Further analysis of soluble cargo levels yielded a complex phenotype. Antibody array analysis showed that several cargo proteins were reduced in Stxbp5 KO platelets. Others were unchanged, and a few, including MMP-9, showed robust increases (Figure 7D). All cargo proteins tested were detectable at some level (Supplemental Figure 4). These data indicate that STXBP5 contributes to the efficacy — and perhaps the selectivity — of granule cargo packaging, but is not essential for the process.

**STXBP5 is important for hemostasis.** The primary function of platelet secretion is in hemostasis. To assess whether STXBP5 contributes to hemostasis, we used 2 in vivo assays. First, a tail bleeding time assay was performed on 5- to 6-week-old mice. Whereas the 19 WT littermates showed an average bleeding time of 226.4 ± 37.3 s, of the 24 Stxbp5 KO mice, only 3 had normal bleeding times; the remainder bled excessively until the study was ended at 10 minutes (Figure 8A). The prolonged tail bleed-
ing of the Stxbp5 KO mice indicates that STXBP5 is required for hemostasis in this transection injury model.

In agreement with the tail bleeding, there was a robust thrombus formation defect observed in Stxbp5 KO mice in response to FeCl₃ injury of the carotid artery. The average time required to form a stable thrombus in WT littermates was 2.7 ± 0.2 minutes, in contrast to 27.7 ± 2.3 minutes for Stxbp5 KO mice (Figure 8B), which indicates that STXBP5 is critical for hemostasis in this arterial injury model.

Platelet counts were not significantly different in Stxbp5 KO and WT littermate mice, although the former exhibited an increase in mean platelet volume (Table 1); therefore, thrombocytopenia is unlikely to be the cause of the bleeding diathesis. The combination of cargo and secretion deficiencies in the Stxbp5 KO platelets could account for the robust bleeding, but since the mouse strain is a global deletion, other processes could precipitate the hemostatic defects. To address whether the loss of STXBP5 in BM-derived hematopoietic cells (e.g., platelets) contributes to the robust bleeding defect observed (Figure 8A and B). Since the Stxbp5 KO animals grafted with WT BM had a normal bleeding profile, it seems unlikely that loss of STXBP5 affects coagulation factors, although this was not directly measured. In summary, these results indicate a role for STXBP5 in platelet granule packing and secretion and in arterial hemostasis.

**Discussion**

The novel findings herein were that STXBP5 was required for normal platelet secretion, granule cargo packaging, and hemostasis. This requirement of STXBP5 for platelet exocytosis diverges from the protein’s proposed role as a negative regulator in neuronal cell, neuroendocrine cell, and EC secretion (21, 24, 39, 47). Our present data indicate that STXBP5 may be important for cardiovascular health, as echoed in recent GWAS in which STXBP5 has been linked to thrombosis (14–20).

Platelet granule release requires the secretory machinery components that are universally used for regulated secretion: SNAREs, Munc18, Rab, and Munc13 (48). Much of the published data suggest that STXBP5 is a negative regulator of secretion, competing with v-SNARE for t-SNARE binding. As in those prior studies, we showed here that STXBP5 interacted with t-SNARE–containing complexes and that its presence was exclusive of at least 2 platelet v-SNAREs (Figure 2). However, deletion of STXBP5, as well as inclusion of an anti-STXBP5 antibody into

**Figure 5. Depletion of STXBP5 in platelets affects ATP/ADP release, but not aggregation.** Aggregation (A–C and H–J) and ATP/ADP release (D–G and K–N) were monitored simultaneously in a lumi-aggregometer. Washed platelets (2.0 × 10⁶/µl) from Stxbp5 KO and WT mice were stimulated with 100 µM PAR-4 peptide (A and E), 10 nM A23187 (B and F), 0.1 µg/ml convulxin (C and G), or thrombin (Thr) at 0.025 U/ml (H and M), 0.05 U/ml (I and N), or 0.1 U/ml (J and O) for 3 minutes. (A–C, E–J, and L–N) Representative traces from 1 experiment. (D and K) Mean ± SEM ATP/ADP release from 3 independent experiments. *P < 0.01, 2-way ANOVA.
a permeabilized platelet secretion assay, inhibited rather than enhanced platelet secretion (Figures 4–6 and Supplemental Figure 5). This result raises the question of how STXBP5 could have a positive effect on exocytosis. Studies in *Drosophila* show that loss of STXBP5 prolongs the excitatory junctional currents (EJCs) at neuromuscular junctions (NMJs) (49). This could be due to ectopic vesicle priming (adjacent to active zones) or prolonged fusion pore opening, which suggests that the role of STXBP5 is to spatially restrict vesicle priming and/or fusion. In platelets, spatial granule priming for exocytosis may be critical for efficacious secretion. While our in-suspension secretion assays (Figures 4–6) may be less influenced by a loss of polarization, secretion in a forming thrombus almost assuredly needs to be polarized (50). Thus, STXBP5 may be important for normal thrombosis, and its deletion would cause the hemostasis defects we observed (Figure 8). At this stage, it is unclear why STXBP5 is important for secretion from yeast (25), INS-1E cells (35), or platelets (Figures 4–6); however, its interactions with cytoskeleton (Figure 2E and Figure 3), especially myosin Va (28, 42, 51), may hint at a role in spatially coordinating SNARE complexes for membrane fusion and subsequent secretion. STXBP5 interactions with cytoskeleton could contribute to granule biogenesis by directing the trafficking of cargo proteins to α granules forming in megakaryocytes. The heterogeneity in cargo levels we observed herein (Figure 7 and Supplemental Figure 4) may be indicative of multiple pathways for granule cargo sorting and packaging. Further work will be required to address these potential functions of STXBP5.

GWAS have linked SNPs in *STXBP5* to alterations in vWF levels (14–19) and tPA levels (18). Loss of STXBP5 increases vWF release from ECs (47), but decreases tPA release (20). These results highlight potentially conflicting roles for STXBP5 in ECs, which may relate to which granules are being released. vWF and tPA are enriched in different granules in ECs (52). Combining these 2 effects, heightened vWF and decreased tPA, might be expected to increase thrombotic risk, consistent with the premise of the GWAS. Conversely, an SNP encoding a nonsynonymous substitution in *STXBP5* (N436S) has been linked to increased bleeding in a female population homozygous for the allele (18). The dramatically prolonged bleeding times in the tail transection model and the hemostasis defects in the FeCl₃-induced carotid artery injury model we observed in *Stxbp5* KO mice and in *Stxbp5* KO BM–grafted WT mice are consistent with this prior report and support a connection between STXBP5 and bleeding risk. At this

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### Table 1. Properties of WT and Stxbp5 KO mouse platelets

<table>
<thead>
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<th>WT</th>
<th>Stxbp5 KO</th>
<th>P</th>
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<tr>
<td>Platelet count (×1,000/μl)</td>
<td>824 ± 123</td>
<td>881 ± 101</td>
<td>0.561</td>
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<tr>
<td>Mean platelet volume (fl)</td>
<td>4.20 ± 0.23</td>
<td>6.28 ± 0.10</td>
<td>0.001</td>
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<td>Serotonin (μM/10⁸ platelets)</td>
<td>6.31 ± 0.5</td>
<td>10.64 ± 1.4</td>
<td>0.006</td>
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<tr>
<td>[³H]-Serotonin uptake (cpm/10⁸ platelets)</td>
<td>2,215 ± 224</td>
<td>4,101 ± 545</td>
<td>0.036</td>
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<tr>
<td>PF4 (pg/10⁶ platelets)</td>
<td>1,690 ± 120</td>
<td>545.5 ± 15</td>
<td>&lt;0.0001</td>
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<tr>
<td>β-Hexosaminidase (nMh⁻¹/10⁶ platelets)</td>
<td>54 ± 10</td>
<td>57 ± 11</td>
<td>0.878</td>
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<tr>
<td>Dense granules/platelet⁶</td>
<td>0.46 ± 0.57</td>
<td>0.52 ± 0.57</td>
<td>0.320</td>
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<tr>
<td>α Granules/platelet⁶</td>
<td>7.97 ± 1.80</td>
<td>7.84 ± 1.22</td>
<td>0.453</td>
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P values were calculated using Student’s t-test. ⁴Determined using the fluorescence o-phthaldialdehyde assay (see Supplemental Methods).

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**Table 1. Properties of WT and Stxbp5 KO mouse platelets**
In summary, our data provide a potential explanation for the GWAS (14–19) linking STXBP5 with cardiovascular disease risk. Our findings showed that STXBP5 was present in platelets and was important for cargo release from dense granules, α-granules, and lysosomes as well as for packaging of some cargo into granules. Mice with platelets deficient in STXBP5 displayed robust defects in thrombus formation in 2 arterial hemostasis models, consistent with the granule biogenesis and release defects. Our data add another component to the pathway of protein-protein interactions that culminates in platelet secretion. They also suggest that platelets may be a useful system for understanding how STXBP5 positively affects exocytosis in other systems, perhaps through its associations with cytoskeleton. Moreover, platelet STXBP5 may be a useful diagnostic marker for cardiovascular diseases.
Methods

Antibodies and reagents. Anti-STXBP5 mAb (611296), anti-Rab27a mAb (clone 20.1), anti-PECAM, FITC-conjugated anti-mouse P-selectin, and unconjugated anti-mouse P-selectin were from BD Biosciences. The anti–hLAMP-1 (H4A3) and anti-hCD63 (H5C6) mAbs were purchased from Synaptic System GmbH. PE-conjugated JonA mAb, anti-GP1bβ, and anti GPVI Abs were purchased from Emfret Analytics. Anti-STXBP5 mAb (611296), anti-Rab27a mAb (5′-CTCCGACCTTTCGGTTTTCCTC-3′ and 5′-TTCAACCGTGATGACAAGGC-3′), m-STXBP5 (5′-CTCCGACTTTCGGTTTTCCTC-3′ and 5′-TTCAACCGTGATGACAAGGC-3′), and s-STXBP5 (5′-CTCCGACCTTTCGGTTTTCCTC-3′ and 5′-TTCAACCGTGATGACAAGGC-3′) isoforms (29, 40).

Immunoprecipitation of STXBP5-interacting proteins. Washed platelet suspensions (10⁹ platelets) were lysed with equal volumes of 2% lysis buffer (100 mM HEPES/KOH, pH 7.4; 2% Triton X-100; 2 mM EGTA; 2 mM EDTA; 150 mM NaCl; and 2% protease inhibitor cocktail) on ice for 30 minutes. The lysates were clarified by centrifugation, and the supernatants were precleared with protein G/A sepharose (GE Healthcare). The interacting proteins were immunoprecipitated with anti-STXBP5, anti-Munc18b, or anti–Munc13-4 Abs, followed by incubation with protein G sepharose. The immunoprecipitates were recovered by centrifugation, washed with lysis buffer, and analyzed by SDS-PAGE and IB.

Genotyping of Stxbp5 KO mice. Stxbp5 KO mice on a 50% 129Sv, 25% C57BL/6, and 25% DBA/2 background were generated as previously described (32). Heterozygous embryos of Stxbp5 KO mice were recovered into live mice by the Jackson Laboratory. Genotype was determined by PCR using DNA isolated from tail tip biopsies. The primers used were as follows: Stxbp5 KO forward, 5′-GGGCGCCCGGTTCCTTTTTGTC-3′; Stxbp5 KO reverse, 5′-GCCATGTGGATCAGTTTTCG-3′; WT forward, 5′-TTCTGGCTCCCGGGTCTCG-3′; WT reverse, 5′-TCTCCGCTCCTTACACCATGC-3′. PCR products were 224 bp for the Stxbp5 KO allele and 300 bp for the WT allele.

Measurement of secretion from intact platelets. The secretion assay was carried out as described previously (13); see Supplemental Methods for details. Briefly, washed platelets were labeled with [3H]-serotonin (0.4 μCi/ml) for 1 hour at 37°C. After washing with HEPES/ Tyrode buffer (10 mM HEPES/NaOH, pH 7.4; 5.56 mM glucose; 137 mM NaCl; 12 mM NaHCO₃; 2.7 mM KCl; 0.36 mM KH₂PO₄; and 1 mM MgCl₂) in the presence of 0.2 U/ml apyrase, the platelets were resuspended and adjusted to 2.5 × 10⁴/μl. For titration experiments, the indicated concentrations of thrombin were added, and the reactions were stopped at 1 minute with a 2-fold excess of hirudin. For time course experiments, 0.1 U/ml thrombin was added for the indicated times, and reactions were stopped with hirudin. Supernatants and pellets were recovered after centrifugation at 13,000 g for 10 minutes, and the pellets were resuspended in favor of the supernatant with 0.5% triton X-100. The optical density of the supernatant was then measured at 450 nm.

References

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1 minute, and the pellets were lysed with an equal volume of lysis buffer (PBS, pH 7.4, and 1% Triton X-100) for 1 hour on ice. Both supernatants and pellets were assayed for 3 granule cargo markers: [3H]-serotonin for dense granules by scintillation counting, platelet factor 4 (PF4) for α granules by ELISA, and β-hexosaminidase for lysosomes by colorimetric assay using p-nitrophenyl-N-acetyl-β-D-glucosaminide, as previously described (54). Secretion was then calculated as (supernatant/[supernatant + pellet]) and expressed as a percentage; the analysis yields a measurement of total cargo content (supernatant plus pellet) and allows for assessment of secretion efficacy independent of cargo content.

Immuno-ﬂuorescence microscopy. Platelet preparation and immunostaining were performed as previously described (55), with slight modiﬁcation. Briefly, sterile glass coverslips were coated with 50 μg/ml human ﬁbrinogen for 24 hours at 4°C. Washed platelets were placed onto ﬁbrinogen-coated coverslips for 1 hour at 37°C. Platelets were ﬁxed with 4% paraformaldehyde for 15 minutes and quenched with 50 mM NH4Cl. Cells were rinsed with 10% FBS/PBS and incubated with the indicated primary antibodies in 10% FBS/PBS containing 0.2% saponin O/N at 4°C. After washing with 10% FBS/PBS, cells were incubated with the appropriate ﬂuorophore-conjugated anti-IgG secondary antibody for 2 hours. After washing, some samples were incubated with TRITC-conjugated phalloidin in 10% FBS/PBS with 0.2% saponin. Coverslips were mounted and examined with a LSM 780 confocal microscope (Carl Zeiss), and images were processed using ZEN blue software (Carl Zeiss). Additional imaging was done using a Nikon AIR confocal microscope, and images were processed using NIS-Elements AR 3.2 software (Nikon).

Platelet aggregation and ATP/ADP release. Murine platelets (2.5 × 10^7/μl) were prepared (13), recalcified with 0.7 mM CaCl2, placed into siliconized cuvettes, and stirred for 3 minutes at 37°C at 1,200 rpm. Luciferin-luciferase substrate was added, followed by the indicated agonists, and the percent change in light transmission was measured. Aggregation and ATP/ADP secretion were monitored using a Model 460VS Lumi-Dual-ﬁlter luciferase substrate was added, followed by the indicated agonists, and the percent change in light transmission was measured. Aggregation and ATP/ADP secretion were monitored using a Model 460VS Lumi-Dual-aggregometer, and traces were acquired using a Model 810 Aggro/Link interface with Aggro/Link software (all from Chrono-Log).

Flow cytometry analysis. Washed murine platelets (2 × 10^6) were kept as resting or were stimulated with thrombin (0.1 U/ml) for 1 minute, after which the reaction was stopped with hirudin. After incubation with antibodies (5 μl) for 15 minutes at room temperature, the reactions were diluted 10-fold with HEPES/Tyrode buffer (pH 6.5). The samples were transferred to tubes, and ﬂuorescence intensities were measured using a FACScan ﬂow cytometer and analyzed using CellQuest (BD Biosciences).

Tail bleeding assay. Tail vein bleeding times were determined as previously described (56). Briefly, 5- to 6-week-old mice were anesthetized with ketamine (75 mg/kg i.p.). Tails were transected 3 mm from the tip and immersed in saline at 37°C. The time from incision to bleeding cessation was recorded. Animals were observed for an additional minute to assess rebleeding. Prolonged bleeding was stopped manually after 10 minutes. Statistical analysis was performed using the log-rank test (GraphPad Prism 5).

FeCl3-induced arterial hemostasis model. The FeCl3-induced arterial thrombosis model was as previously described (57). Briefly, mice 8–12 weeks of age were anesthetized with Avertin (0.2 g/kg i.p.) and placed on a 37°C heating pad. The left carotid artery was exposed, and a Doppler TS420 ﬂowmeter (0.5VB; Transonic System Inc.) was placed on the artery to monitor blood ﬂow. Thrombus formation was induced by placing a small piece of ﬁlter paper, saturated with 5% FeCl3 solution, on the vessel for 3 minutes. Time from application to cessation of ﬂow was measured. Experiments were terminated at 30 minutes. Statistical analysis was performed using the log-rank test (GraphPad Prism 5).

BM transplantation mouse model. BM transplantation was performed as previously described (58), with some modiﬁcation. Briefly, BM harvested from femurs and tibias of 6-week-old WT or Stxbp5 KO mice was resuspended with 10 mM HEPES, pH 7.4 buffer containing 25 U/ml heparin and 5% FBS and adjusted to 5 × 10^7 cells/ml. The cell suspension (0.1 ml) was injected into the retroorbital sinus of lethally irradiated mice. After 6 weeks of recovery, tail bleeding and FeCl3-induced hemostasis assays were performed. Statistical analysis was performed using the log-rank test (GraphPad Prism 5).

Subcellular fractionation of platelets. Human platelets were resuspended in HEPES/Tyrode buffer (pH 7.4) and treated with or without 0.1 U/ml thrombin for 5 minutes. The resting and activated platelets were disrupted by 5 freeze-thaw cycles. After disruption, the unbroken cells were removed by centrifugation at 700 g for 5 minutes, and the supernatants were fractionated by ultracentrifugation at 100,000 g for 1 hour. The supernatant (cytosol) was collected, and the resulting pellets were solubilized with 1% Triton X-100, incubated on ice for 15 minutes, and then subjected to centrifugation at 100,000 g for 1 hour. The supernatant (Triton X-100-soluble fraction) was collected, and the resulting pellets were solubilized with 1% n-octyl-β-D-glucopyranoside, incubated on ice for 15 minutes, and then subjected to centrifugation at 100,000 g for 1 hour. The supernatant (n-octyl-β-D-glucopyranoside–soluble fraction) was collected. The detergent-insoluble pellets were solubilized in SDS-PAGE loading buffer. The supernatants (soluble fractions) and pellets (detergent-insoluble fractions) were subjected to SDS-PAGE and transferred to nitrocellulose membranes for Western blotting. The membranes were washed 3 times and incubated with HRP-conjugated streptavidin for 30 minutes. After washing the membranes 3 times, the signals for each array spot were detected with Supersignal West Dura substrate (Thermo-Scientific) using a Chemidoc MP System (BioRad). The array experiments were run in duplicate. Fluorescence intensities for each spot were measured, background was subtracted, and the Stxbp5 KO/WT ratio was calculated and plotted using SigmaPlot (version 12.0; Systat Software Inc.). Under these conditions, spots for 3 proteins — SDF-1, PF4, and angiopoietin 1 — were saturated, and thus failed to yield quantitative data (Supplemental Figure 4). These were excluded from analysis.

Statistics. Data from bleeding time and occlusion assays were analyzed by log-rank test. Data from secretion assays and FACs-based...
experiments were analyzed by 2-way ANOVA. A 1-tailed Student’s t test was used to analyze the properties of platelets from Stxbp5 KO and WT mice. A P value less than 0.05 was considered significant.

Study approval. Animal procedures were approved by the IACUC of University of Kentucky. Human samples were from anonymized units; thus, no IRB approval or informed consent was required.

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