Cytoskeletal Mechanics of Proplatelet Maturation and Platelet Release

Citation

Published Version
doi:10.1083/jcb.201006102

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Cytoskeletal mechanics of proplatelet maturation and platelet release


Megakaryocytes generate platelets by remodeling their cytoplasm into long proplatelet extensions, which serve as assembly lines for platelet production. Although the mechanics of proplatelet elongation have been studied, the terminal steps of proplatelet maturation and platelet release remain poorly understood. To elucidate this process, released proplatelets were isolated, and their conversion into individual platelets was assessed. This enabled us to (a) define and quantify the different stages in platelet maturation, (b) identify a new intermediate stage in platelet production, the preplatelet, (c) delineate the cytoskeletal mechanics involved in preplatelet/proplatelet interconversion, and (d) model proplatelet fission and platelet release. Preplatelets are anucleate discoid particles 2–10 µm across that have the capacity to convert reversibly into elongated proplatelets by twisting microtubule-based forces that can be visualized in proplatelets expressing GFP–β1-tubulin. The release of platelets from the ends of proplatelets occurs at an increasing rate in time during culture, as larger proplatelets undergo successive fission, and is potentiated by shear.

Introduction

Platelet production represents the final stage of megakaryocyte development. This process, during which a giant endomitotic cell converts into 10^2–10^3 individual platelets, is highly specialized and has great clinical significance. Thrombocytopenia is a major clinical problem encountered across several conditions, including immune (idiopathic) thrombocytopenic purpura, myelodysplastic syndromes, chemotherapy-induced thrombocytopenia, aplastic anemia, human immunodeficiency virus infection, and major cardiac surgery, among others. The magnitude of the problem is not trivial. Platelet transfusions total well over 10 million units per year in the United States, and their steady increase in demand continues to challenge the U.S. blood bank community (Sullivan et al., 2007). A better understanding of the mechanisms of platelet formation will likely lead to improved therapies for thrombocytopenia. Furthermore, the ability to control in vitro megakaryocyte expansion and maturation into platelets could result in an important source of platelets for transfusion.

The proplatelet model of platelet formation recognizes that differentiated megakaryocytes extend long, branching processes, designated proplatelets, which are comprised of platelet-sized swellings in tandem arrays that are connected by thin cytoplasmic bridges. Proplatelets have been identified both in vitro and in vivo (Leven, 1987; Leven and Yee, 1987; Tablin et al., 1990), and proplatelet-producing megakaryocytes yield platelets that are structurally and functionally similar to blood platelets (Behnke, 1969; Becker and De Bruyn, 1976; Radley and Scurfield, 1980; Tavassoli and Aoki, 1981; Choi et al., 1995; Italiano et al., 1999). Mice lacking distinct hematopoietic transcription factors have severe thrombocytopenia and fail to produce proplatelets in culture, underscoring the correlation to platelet biogenesis in vivo (Shivdasani et al., 1995; Shivdasani and Orkin, 1996; Lecline et al., 1998; Shivdasani, 2001). Because of the
dramatic morphological changes that occur during proplatelet production, the cytoskeletal mechanics that drive these transformations have been the focus of many studies. Nevertheless, the terminal stages of proplatelet maturation and platelet release remain poorly understood. This is due in part to significant limitations in the field, such as the asynchronous maturation of hematopoietic stem cells in culture and our inability to synchronize proplatelet production. Megakaryocyte cultures always contain a complex mix of hematopoietic stem cells, immature megakaryocytes, proplatelet-producing megakaryocytes, released proplatelets (which can range dramatically in size and shape), and platelets (Behnke and Forer, 1998; Italiano et al., 2007). As there are currently no methods available to isolate the multiple intermediate stages in platelet release, most studies to date have focused on the qualitative aspects of megakaryocyte maturation.

Physiological evidence of proplatelet production has been supported by multiple images of proplatelets extending into the sinusoidal blood vessels of the bone marrow (Behnke, 1969; Becker and De Bruyn, 1976; Kessel and Kardon, 1979). Nevertheless, these represent only static snapshots of megakaryocyte maturation in situ and have yielded competing mechanistic models of platelet release. Junt et al. (2007) recently used live imaging with multiphoton intravital microscopy to visualize platelet production in vivo. Although they demonstrate that bone marrow megakaryocytes will extend proplatelets and release fragments into the vasculature, the observations they present raise questions of their own. For example, most of the shed megakaryocyte fragments appear to greatly exceed platelet dimensions, suggesting that proplatelet morphogenesis continues in peripheral blood. Because blood is moving, individual platelet release may be assisted by intravascular shear forces as proplatelets enter and become trapped in capillaries. The largest capillary bed is in lung, and it has been reported that proplatelet counts are higher in prepulmonary vessels compared with postpulmonary vessels (Handagama et al., 1987), whereas platelet counts are higher in the latter. However, evidence of a dependence of proplatelet fragmentation into platelets on hydrodynamic forces is missing.

In vivo observations that validate the proplatelet model and provide clues into the final steps of platelet production also raise several questions: how do proplatelets mature into individual platelets, is there an intermediate structure as proplatelets convert into platelets, what cytoskeletal forces are involved, and does vascular shear regulate individual platelet release? This study defines the multiple intermediate stages in proplatelet maturation and begins to identify relevant mechanistic interactions leading to platelet release from proplatelets.

Results

Characterization of the morphological stages as proplatelets mature into platelets

To study distinct stages in platelet production in vitro, released proplatelets were isolated by a novel centrifugation and gradient sedimentation protocol (Fig. S1). Enriched proplatelet populations were prepared from megakaryocyte cultures at times of maximal proplatelet elaboration and characterized for the presence/absence of a nucleus, morphology, and size (Fig. 1 A) after double staining for nuclei and tubulin (microtubules). This enabled us to define and quantify different stages in platelet maturation and identify a new intermediate stage in platelet production, the proplatelet. Preplatelets are anucleate discoid particles considerably larger (2–10 µm) than platelets that have the capacity to reversibly convert into proplatelets (anucleate bead strings with platelet-sized tear drops at each end) during cell culture. Fig. 1 B shows the distribution of cellular elements in a fresh preparation after the removal of most megakaryocytes; a few megakaryocytes (<1% of the total number of objects) contaminate the cultures, although immature intermediates (proplatelets and preplatelets) and platelets make up the bulk of the culture. Proplatelets were subdivided into two groups by their perimeter, large (>50 µm) or small (30–50 µm), with large proplatelets initially dominant. Preplatelets and platelets were distinguished by their diameters (>2 µm or ≤2 µm, respectively). Large preplatelets were subdivided into four groups based on their diameters (8–10, 6–8, 4–6, or 2–4 µm). These were quantified and normalized to total proplatelet/preplatelet (PP) counts to account for variability in density between different preparations. Proplatelets and preplatelets were equally distributed and comprised ~62% of the total number of objects. The majority (69%) of proplatelets have small (2–4 µm) diameters, approaching the size of mature platelets. The rest of the preplatelets were distributed as follows, based on their diameters: 4–6 (25%), 6–8 (4%), and 8–10 µm (2%). EM revealed that preplatelets are discoid because they have a cortical microtubule band and contain materials destined for platelets, such as secretory granules, invaginated membranes, and mitochondria (Fig. 1 C). This is expected if larger PPLT progenitors generate multiple smaller intermediates, which themselves go on to release two or more individual platelets. From estimates of cytoplasmic volume based on EM images, the largest preplatelets carry sufficient material to generate 6–20 mature platelets. 37% of the elements in the enriched proplatelet culture were platelet sized and appeared identical to platelets from mouse blood after tubulin staining. These were presumably left over after the final centrifugation step and represent platelets generated at an earlier point in culture.

Proplatelets/preplatelets can mature into platelets in vivo

Although proplatelet release (Junt et al., 2007) suggests fragmentation into platelets in blood, this supposition has not ever been observed or formally demonstrated. To establish that platelet release/maturation can occur within the blood vasculature, freshly enriched preplatelet/preplatelet isolates were 5-chloromethylfluorescein diacetate (CMFDA) labeled (Fig. 2, A and C [top]) and transfused into mice. CMFDA-labeled blood platelets were used as a control in parallel transfusions. Fig. 2 C (bottom) shows combined immunofluorescence and differential interference contrast (DIC) photographs of the platelet fraction from the blood of these mice 2 h after the proplatelet or platelet transfusion. CMFDA-labeled platelets recovered in the blood of recipient mice are identified, and when proplatelets
Further analysis of the flow cytometry data reveals that the PP fraction is rapidly sequestered after its infusion into mice; e.g., PPs are not found in blood in the initial 1:1 ratio to platelets present in the samples. In addition, the increase in CMFDA-labeled platelet counts is faster in vivo than occurs for platelets in culture (Fig. S2, B, C, and E), suggesting that blood flow–induced shear stress and/or receptor-mediated signaling may accelerate platelet release.

Platelet release in culture

The variety of different-sized preplatelets in the proplatelet culture suggested to us that we were observing an ongoing maturation program and that by studying it in vitro, we could establish precursor–product relationships between the various intermediates. We first qualified proplatelet fission (Fig. 3 A) and platelet release (Fig. 3 B) in the proplatelet cultures by video-enhanced DIC microscopy. During this process, the connection between swellings on proplatelets thins dramatically and then snaps, at which point the fragmented ends retract toward their daughter cells.

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Figure 1. Identification and quantification of intermediates in platelet release by immunofluorescence microscopy. The released proplatelet-enriched fraction and washed mouse platelets (control) were probed with a rabbit polyclonal antibody against detyrosinated tubulin and analyzed by immunofluorescence microscopy for different-sized objects. Intermediates in platelet release were categorized based on perimeter (proplatelets) or diameter (megakaryocytes, preplatelets, and platelets). (A) Representative pictures of a day 5 proplatelet-enriched culture before (left) and after (middle) thresholding of anti-tubulin–labeled intermediates using MetaMorph software and washed mouse platelets (0.5–2-µm diameter; right). (B) Relative distribution of intermediates at day 5 of culture after proplatelet enrichment. (C) Representative pictures of the tubulin cytoskeleton of mouse preplatelets (2–10-µm diameter; immunofluorescence microscopy; inset), their ultrastructure (thin-section EM; bottom), and cytoskeleton (rapid-freeze EM; top).

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were infused, this demonstrates platelet formation in blood. To quantitate platelet release, CMFDA-labeled proplatelets were transfused into mice, and blood samples were collected at regular intervals over a period of 72 h, commencing <2 min after infusing the proplatelets. Platelet-rich plasma (PRP) was isolated from the obtained blood samples, and the PPs and platelet-sized fractions were dissected and analyzed by flow cytometry (Fig. 2, A and B; Baker et al., 1997; Hoffmeister et al., 2003a). The percentage of labeled platelets in the blood at the first time point (~2 min) after transfusion is used as 100%. When platelets are transfused, they rapidly distribute in the blood volume and their blood concentration decreases thereafter, depending on the circulatory lifespan of the platelets (half-life, ~1.5–2 d in mice). However, when the immature PPs were transfused, there was a time-dependent increase in the number of labeled platelet-sized particles in blood as the infused proplatelets convert into platelets. Platelet release from the infused proplatelets was maximal by 12 h, after which the labeled platelet numbers begin to decrease, as expected again from the platelet lifetimes in blood.
In certain thin-section electron micrographs, a small constriction, resembling a cleavage furrow (similar to that described previously; Schwertz et al., 2010), is found in the proplatelet shaft (Fig. 3 C).

Platelet production was quantified using the combination of flow cytometric analysis and immunofluorescence microscopy to identify mature platelet-sized particles (2 µm in diameter) expressing the platelet-specific glycoprotein IX (GPIX) on their surface and/or having a cortical microtubule coil in the cultures. Mouse blood platelets served as size controls for these experiments (Fig. S2 A). Morphometry and flow cytometry showed that the number of large PP progenitors decreased...
Figure 3. Direct visualization of proplatelet/platelet release in culture. (A and B) Isolated proplatelets were diluted with a semisolid culture medium and maintained in custom BSA-coated chambers at 37°C. They were examined on an inverted microscope, and frames were captured at 30-s intervals. (A) The separation of proplatelet cytoplasm and associated release of a shorter proplatelet fragment. The arrows highlight the site of proplatelet division. (B) The release of an individual platelet (arrows) from the end of a larger released proplatelet. (C and D) Thin-section electron micrographs showing the ultrastructure of a barbell-shaped proplatelet in the process of platelet release. Black arrows highlight the formation of a constricted region resembling a cleavage furrow along the long shaft of a cultured proplatelet. (C, inset) A higher magnification view of the boxed area is shown. (D) A similarly shaped barbell proplatelet immediately after cleavage. The arrow highlights the site of proplatelet division.
Having established a precursor–product relationship between platelet release
Mechanisms of proplatelet maturation and
suggests that the reorganization of microtubules plays an essen-
tion during their interconversion between preplatelet and barbell
mediates in platelet production undergo a dramatic reorganiza-
tion after taxol or nocodazole incubations appear in Fig. 4 D. These
controls. Fig. 4 C illustrates a shift in the distribution of the re
(binned by object area and normalized to day 5 counts after 2,
4, 24, 48, and 72 h in culture and demonstrates proplatelet fission and platelet release at an
increasing rate in time.

Reversible conversions between preplatelets and proplatelets
Because the intermediates in platelet production distribute evenly
between elongated proplatelets and discoid preplatelet in the cul-
tures, we hypothesized that the two forms were interrelated. To test
this hypothesis, we asked whether manipulation of microtubules
within these structures could convert barbell proplatelets to
preplatelets and vice versa. Released proplatelet cultures were incu-
bated at either 37°C (normal control), 4°C for 1 h to depolymerize
microtubules, or at 4°C for 1 h and then 37°C for 1 h to depoly-
merize and repolymerize microtubules. Fig. 4 displays log differ-
ence in total proplatelet, preplatelet, and platelet counts at 4°C
(Fig. 4 A) and 4–37°C (Fig. 4 B) relative to 37°C control. Counts of
proplatelets and preplatelets were performed as previously de-
dscribed, and all values were normalized to 37°C controls. Data were
subject to one-way analysis of variance (ANOVA) for three inde-
pendent samples and Tukey honestly significant difference (HSD)
analysis (P < 0.01 and P < 0.05). Depolymerization of tubulin at
4°C significantly shifted the proplatelet population to preplatelet
forms (Fig. 4 A). The proplatelet population returned to normal
when the samples were returned to 37°C (Fig. 4 B), indicating that
the proplatelet structure is a result of tubulin polymerization and
microtubule organization about its midbody.

This observation was confirmed using a second method of
microtubule manipulation, wherein released proplatelet cul-
tures were incubated at 37°C in the presence of a microtubule-
stabilizing agent (5 µM taxol) or a tubulin-depolymerizing agent
(5 µM nocodazole) for 1 h. Counts of proplatelets and pro-
platelets were performed, and all values were normalized to no-drug
controls. Fig. 4 C illustrates a shift in the distribution of the re-
leased proplatelet culture population toward smaller proplatelet
or preplatelet forms in the presence of taxol or nocodazole, respec-
tively. Representative pictures of proplatelet-enriched cultures
after taxol or nocodazole incubations appear in Fig. 4 D. These
results suggest that the microtubule cytoskeleton of inter-
mediates in platelet production undergo a dramatic reorganiza-
tion during their interconversion between proplatelet and barbell
proplatelet forms. Moreover, the pharmacological regimen used
suggests that the reorganization of microtubules plays an essen-
tial role in this morphogenesis.

Mechanisms of proplatelet maturation and
platelet release
Having established a precursor–product relationship between
proplatelets–preplatelets and proplatelets–platelets, we investigated
the underlying mechanisms. Three types of behaviors were studied
in detail: (1) the proplatelet–preplatelet interconversions, (2) fission
of small proplatelets into platelets, and (3) shear-facilitated
proplatelet fission and platelet release. Proplatelets and preplate-
lets are distinguished from their elongated or discoid shapes, re-
spectively. However, both have prominent cortical microtubule
bundles. In preplatelets, these bundles rim the cytoplasmic surface
of the membrane on the disc face. In proplatelets, the bundles also
rim the cell membranes of the bulbous particles, but they collapse
together and interact along the shafts. The exponential accumula-
tion of smaller PPs and platelets in our culture system over time
implies a model in which larger proplatelet progenitors undergo
continuous fission, producing an increasing number of sequential
platelet release sites.

Direct visualization of microtubule dynamics
during the conversion of proplatelets to
barbell proplatelets
To visualize the microtubule cytoskeleton directly during pre-
platelet to barbell proplatelet conversion and to confirm this
relationship between the two intermediate structures, cultured
megakaryocytes were retrovirally directed to express GFP–
β1-tubulin. Released proplatelet fractions were isolated, and GFP–
β1-tubulin–labeled preplatelets were monitored by fluorescence
time-lapse microscopy. Fig. 5 A depicts a representative proplate-
let of ~7 µm in diameter over a period of 4 min. In this time, the
oval marginal band was observed to twist about its center several
times in a clockwise fashion to ultimately yield a barbell-shaped
proplatelet with two well-defined platelet-sized (2-µm diameter)
microtubule loops at each end. This was confirmed by thin-
section EM (Fig. 5 B). Fig. 5 C shows the microtubule cyto-
skeleton twisting about the preplatelet center to yield a “figure 8”
structure comparable with Fig. 5 A (1 min) and suggests an
intermediate stage in proplatelet to proplatelet interconversion.

To establish whether microtubules continue to polymerize
throughout released proplatelets once defined microtubule
loops have formed, mouse megakaryocyte cultures were retro-
virally directed to express EB3-GFP. EB3-GFP localizes only
to polymerizing microtubule plus ends in a characteristic comet
staining pattern with a bright front and dim tail (Fig. S3). Fig. S3
shows the first frame from Video 4, a time-lapse video of a
cultured proplatelet expressing EB3-GFP. Multiple comets are
observed moving bidirectionally in the cytoplasmic bridge
and within the microtubule coil at the ends of the proplatelet,
confirming continued dynamic assembly and reorganization of
microtubule coils at a late stage of proplatelet development.
Comet movement rates are estimated to be ~8.9–12.3 µm/min.

Multivesicular bodies (MVBs) are present
and granules continue to sort in released
proplatelet/preplatelet intermediates
The biogenesis and distribution of platelet-specific granules into
nascent platelets are essential to platelet production. In mega-
karyocytes, MVBs represent a developmental stage in
granule and dense-granule maturation (Heijnen et al., 1998; Youssefian
and Cramer, 2000). Indeed, differences in intragranular protein
distribution of MVBs, α-granules, and dense granules have been
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[Image 50x256 to 548x732]

[561x25]867

[346x25]The final stages of platelet production

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(311x126) Figs. 6 A and 5 S5), which may suggest ongoing granule biogenesis in these cells.

Transport of organelles along proplatelets involves movement along microtubules and translocation of linked microtubules relative to one another (Richardson et al., 2005). Barbell proplatelets have a dynamic microtubule cytoskeleton that continues to assemble and reorganize during late-stage platelet development.

Figure 4. Preplatelets reversibly convert into proplatelets using microtubule-based forces. (A and B) Preplatelet-enriched fractions were probed with a rabbit polyclonal antibody against detyrosinated tubulin and analyzed by immunofluorescence microscopy for different-sized objects. Samples were incubated at 37°C (normal control), 4°C for 1 h, or 4°C for 1 h and returned to 37°C for 1 h. All values were normalized to the 37°C controls. (A) Depolymerization of tubulin at 4°C shifted the proplatelet population into preplatelet forms. *, P < 0.05; **, P < 0.01. Arrows indicate values compared and significance level of difference. (B) The proplatelet population returned to normal upon repolymerization of tubulin at 37°C. Data were subject to one-way ANOVA for three independent samples and Tukey HSD analysis. (C) Released proplatelet/platelet fraction from second gradient sedimentation probed with a rabbit polyclonal antibody against detyrosinated tubulin and analyzed by immunofluorescence microscopy for different-sized objects. Distribution of proplatelet and preplatelet forms after 1 h in culture with 5 µM taxol (promotes microtubule polymerization; left), a vector control (middle), or 5 µM nocodazole (promotes microtubule depolymerization; right). Microtubule stabilization and depolymerization shifted the population toward proplatelet and preplatelet forms, respectively. (D) Representative pictures of cultured intermediates after taxol (proplatelet) or nocodazole (preplatelet) incubations.
isolated PPs were maintained in culture under static conditions intermediates could be accelerated by circulatory shear forces, and platelet release in vitro

Shear forces accelerate proplatelet fission and platelet release in vitro

To determine whether platelet production from released PP intermediates could be accelerated by circulatory shear forces, isolated PPs were maintained in culture under static conditions or with continuous shear (≈0.5 Pa) for 2 h and analyzed by immunofluorescence microscopy and flow cytometry at 20-min intervals. Fig. 7 (A–C) shows composite images of the proplatelet culture after 0, 60, and 120 min of shear. Compared with the no shear control, platelet numbers increased, whereas the number of proplatelets decreased over time (Fig. 7 D). Platelet and PP progeny (1–137 µm²; Fig. 7 E) and proplatelet progenitors (138–227 µm²; Fig. 7 F) were binned by size (area), and their relative counts over time were spread across multiple bins to resolve the mechanism of platelet release. The data describe an inverse relationship between smaller and larger object counts that suggests dynamic proplatelet fission and continuous platelet release under shear with time. Flow cytometric analysis of cultured samples agree with immunofluorescence microscopy data and reveal a significant decrease in the number of large proplatelets and PP intermediates (small ProPLTs) after 2 h relative to no shear control (Fig. 7, G and H). Fig. 8 summarizes the model of platelet production from proplatelets supported by these experiments.

Discussion

The presence of proplatelets in blood implies that they fragment into individual platelets. To evaluate the mechanisms by which released proplatelets mature platelets and to identify intermediate stages in this process, we developed a novel centrifugation and gradient sedimentation protocol to separate megakaryocytes and residual megakaryocyte cell bodies from released proplatelets. This enabled us to define and quantify different stages in proplatelet maturation and platelet release, relate these temporal changes to cytoskeletal rearrangements, and begin to describe some of the mechanistic events that ultimately lead to platelet release.

To define the relative distribution of these different-sized objects over time and to place the appearance and accumulation of individual platelets in a temporal context, intermediates in platelet release were categorized by their morphologies and size. This allowed changes in distribution to be tracked over a period of 5 d in culture. In addition to mature discoid platelets and elongated proplatelets, we identified a large, intermediate discoid stage in platelet production, which we have named the “proplatelet.” Preplatelets are large anucleate discs, 2–10 µm in diameter, that have a thick cortical microtubule coil and retain the capacity to reversibly convert into barbell-shaped platelets. Continued bidirectional polymerization of microtubules at each end of the barbell proplatelet forms two well-defined platelet-sized (2-µm diameter) microtubule loops at each end. These become two individual platelets after a fission event. Interestingly, interconversion between proplatelet and proplatelet forms occurs only at proplatelet diameters 2–10 µm across. Thus, proplatelets represent an intermediate stage in platelet production that may be responsible for regulating platelet size. Although larger microtubule coils may undergo twisting to accommodate continued microtubule polymerization/elongation within a constrained volume, forming barbell proplatelets, smaller, more constricted microtubule coils are unable to do so. As megakaryocyte fragments divide (thus becoming smaller), this results in a size limit beyond which new platelets are no longer capable of fission and may therefore provide an artificial margin from which platelets can be classified as distinct from their progenitors.

This raised the question of whether organelles continue to sort between platelet-sized swellings in these structural intermediates. To resolve the localization and distribution of secretory granules in the preplatelet and released proplatelet during interconversion, cultures were either labeled with a fluorescent human fibrinogen conjugate (taken up and stored in α-granules) or probed for serotonin (present in dense granules) and analyzed by immunofluorescence microscopy. The distribution and dynamics of the labeled α-granules were followed using time-lapse fluorescence microscopy and demonstrate ongoing, bidirectional α-granule movement during preplatelet–proplatelet conversion (Fig. 6 B). Video 1 also demonstrates the elongation that precedes the fission-like process that accompanies preplatelet to barbell proplatelet conversion. α-Granules localize to the microtubule cytoskeleton and are generally confined to the periphery of the cell. Fig. 6 C illustrates continued and bidirectional translocation of fluorescently labeled α-granules in a barbell proplatelet over a period of 36 min. Red dots highlight α-granule movement toward the top end of the proplatelet, whereas green dots highlight movement toward the bottom end. Labeled organelles moved bidirectionally along the microtubule tracks of cytoplasmic bridges and cortices of developing proplatelets at a rate of ≈0.13–0.26 µm/min, implying continued reorganization of platelet contents through late stages of the maturation process. This is also true of dense granules, which distribute within the preplatelet and along the cytoplasmic bridges and bulbous tip of released proplatelets (Fig. 6 D). Like the α-granules, these continue to translocate throughout maturation.

Shear forces accelerate proplatelet fission

Although larger microtubule coils may undergo twisting to accommodate continued microtubule polymerization/elongation within a constrained volume, forming barbell proplatelets, smaller, more constricted microtubule coils are unable to do so. As megakaryocyte fragments divide (thus becoming smaller), this results in a size limit beyond which new platelets are no longer capable of fission and may therefore provide an artificial margin from which platelets can be classified as distinct from their progenitors.
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These subsequently decrease in size over time to that of normal platelets as the count returns to baseline (Patel-Hett et al., 2008). When CMFDA-labeled proplatelets are transfused into recipient mice, platelets rapidly release for a period of 12–24 h. In vitro, proplatelets slowly mature into multiple individual platelets over a 5-d culture period, as total proplatelet and preplatelet counts decrease about sevenfold, whereas platelet counts increase about fourfold. Thus, this intermediate stage may correlate to the young, large platelets found during recovery from acute thrombocytopenia, such as that in immune-mediated platelet destruction (Patel-Hett et al., 2008), and they may represent the submegakaryocyte fragments observed previously in PRP (Behnke and Forer, 1998).

As proplatelets are not generally seen at concentrations comparable with those of platelets in healthy human and mouse
Figure 7. Shear force promotes proplatelet fission and platelet release. [A–H] Proplatelets released from fetal liver–derived megakaryocytes were cultured for 2 h in the presence or absence of shear (0.5 Pa). Every 20 min, samples were removed and probed with a rabbit polyclonal antibody against β1-tubulin and analyzed by immunofluorescence microscopy for different-sized objects (A–D) or labeled with a CD42a-specific, FITC-conjugated antibody and analyzed by flow cytometry (G and H). (A–C) Representative micrographs of the culture after 0 (A), 60 (B), and 120 (C) min of shear. (insets) High magnification views of the composite images are shown. (D) Compared with no shear controls, platelet numbers increased over time, whereas proplatelet numbers decreased (n = 4). (E and F) Representative quantification of culture intermediates under shear with time. Platelet and PP progeny (cells of area = 1–137 µm²; E) and proplatelet progenitors (138–227 µm²; F) were binned by size (area), and their relative counts over time were spread across multiple bins to resolve the mechanism of platelet release. The data describe an inverse relationship between smaller and larger object counts that reveal dynamic proplatelet fission and continuous platelet release under shear with time. (G) Flow cytometric analysis of cultured proplatelet intermediates under shear with time (n = 3). (H) Representative quantification of cultured proplatelet intermediates by flow cytometry. Samples support immunofluorescence microscopy data and reveal a significant decrease in the number of large proplatelets and PP intermediates (small ProPLTs) after 2 h relative to no shear control. Error bars indicate mean ± standard deviation.

whole blood smears, it stands to reason that the rate of platelet production in our culture system remains relatively low as compared with suspected platelet release rates in vivo. Modeling of this effect revealed that during cell culture, platelets are generated at an increasing rate in time, and large proplatelets undergo continuous fission to produce more ends from which platelets
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Figure 8. Proplatelet fission model of platelet release. Model of platelet production suggested by these experiments and previous studies (see Results). (A) Released proplatelets undergo successive rounds of fission along their midbody and at their ends. This process is mediated by the formation of a cleavage furrow at the point of division and results in platelet release from proplatelet ends at an increasing rate in time as more ends become available after each fission event. Shear promotes proplatelet fission and drives platelet release. (B) Barbell proplatelets of ~30–50-µm perimeter reversibly convert into preplatelets. This process is driven by twisting microtubule-based forces and may represent a novel mechanism of microtubule reorganization and granule redistribution after each fission event. (C) During barbell proplatelet formation, dynamic and bidirectional assembly and reorganization of microtubule coils mediate platelet cytoskeleton arrangement as α- and dense granules track to distal proplatelet tips. Platelets release from proplatelet ends after the final fission event.

are released. Indeed, relatively weak hydrodynamic forces of maximally 0.5 Pa were found to promote proplatelet fission, which is likely necessary in regulating the rate of platelet release in vivo. Flow cytometric analysis of CMFDA-labeled proplatelets transfused into live mice supports this hypothesis and suggests that blood-flow–induced shear stress may contribute to platelet release in vivo by promoting proplatelet fission events. Indeed, observations that proplatelet counts are higher in pre-pulmonary than in postpulmonary vessels (Handagama et al., 1987), whereas platelet counts are higher in the latter, imply that shear forces act on released proplatelets in the vasculature to mediate platelet production.

The geometric decay of larger proplatelet progenitors and accumulation of smaller PPs and released platelets in our culture system over time (under both static and continuous shear conditions) implies that platelets are predominately released from proplatelet ends as proplatelets undergo continuous fission in culture. Therefore, proplatelets contain all of the programming and material required to make and release platelets, which is in accordance with the observations that bone marrow megakaryocytes extend and release large cellular processes, exceeding platelet dimensions, into blood (Junt et al., 2007).

Nevertheless, how small proplatelets, barbell-shaped proplatelets, and platelets release from larger proplatelets has never been detailed. Our video-enhanced DIC images of proplatelets in culture reveal that large proplatelets divide into shorter proplatelets and release individual platelets. As a proplatelet elongates, its long, narrow shaft will sometimes snap, dividing the structure into two pieces. This snapping and retraction is characteristic of the release of mechanical tension being applied along the process by internal cytoskeletal motors. Measured rates of proplatelet fission and platelet release show that cleavage events
occur continuously throughout the different intermediate stages of platelet production, resulting in mixed platelet populations of various different sizes.

Proplatelets must not only produce and replicate the specialized cytoskeleton of the mature platelet, but they must also load each platelet with a reproducible and appropriate allotment of organelles and granules essential for their hemostatic function. Our experiments demonstrate the presence of MVBs in late-stage intermediates, which represent a developmental step in α- and dense-granule maturation. One of the most surprising findings is that even at the very final stages of platelet production, when two putative platelets are connected by a cytoplasmic bridge, the granule content of the platelet is still being adjusted. It has recently been shown that platelets contain distinct subpopulations of α-granules that undergo differential release during activation (Italiano and Battinelli, 2009). Interconversion between barbell proplatelet and preplatelet forms might therefore represent a novel mechanism of granule redistribution and sorting before platelet release from proplatelet ends.

In summary, this study defines the multiple intermediate stages in proplatelet maturation and identifies several relevant mechanical interactions, which govern individual platelet release. Our understanding of the final stages of platelet production is still far from perfect, and there remain many questions that still need to be answered: (a) what factors and signal transduction pathways are involved in reorganizing the microtubule cytoskeleton to mediate PP interconversion and platelet release, (b) how do shear forces in the circulation contribute to this process, (c) is platelet production in vivo a result of sequential liberation from proplatelet ends or a product of successive fission of the released proplatelet, and (d) how do preplatelets identified in culture correlate with immature platelets observed in thrombocytopenia and large platelets observed in many macrothrombocytopenias? Nevertheless, the development of new methods to isolate and quantify the multiple intermediate stages in platelet release holds promise that these questions can now begin to be addressed.

Materials and methods

Megakaryocyte suspension cultures
Mouse fetal liver cells were recovered on embryonic day 13.5. Single-cell suspensions were prepared by successive passage through 22- and 25-G syringes and cultured for 4 d in DME (Invitrogen) supplemented with 10% fetal calf serum, 2 mmol/liter glutamine, 50 U/ml penicillin, and 50 µg/ml streptomycin at 37°C and 5% CO2.

The megakaryocyte pellet was dispersed using 0.1 µg/ml purified recombinant mouse c-Mpl ligand (day 0; Lecine et al., 2000). All experiments were performed with freshly isolated megakaryocytes. Megakaryocyte cultures were allowed to sediment for 1 h, during which intermediate populations of megakaryocytes were localized to the BSA fraction, whereas released proplatelets and individual platelets remained in the top (culture media) fraction. This top-most layer was removed and centrifuged (200 g for 5 min) to separate released proplatelet (pellet) and platelet (supernatant) fractions. Samples were washed and resuspended in culture media. Cultures were kept at 37°C and 5% CO2 throughout.

Immunoﬂuorescence microscopy

Mouse megakaryocytes, culture intermediates, and whole blood platelets were purified and probed as previously described (Patel-Hett et al., 2008). In brief, samples were ﬁxed in 4% formaldehyde and centrifuged onto 1 µg/ml poly-lysine–coated coverslips, permeabilized, and blocked (Italiano et al., 2003) before antibody labeling. Released proplatelet-enriched fractions were incubated with a rabbit polyclonal antibody against dextranized tubulin (SuperGlu; provided by C. Bolinski, Columbia University, New York, NY) or a rabbit monoclonal antibody against serotonin (YCS5/45; Abcam) for dense-granule visualization and treated with secondary goat anti–rabbit antibody conjugated to an Alexa Fluor 488 (Invitrogen). DAPI (Sigma-Aldrich) was used to label the megakaryocyte nucleus. Samples were examined with a microscope (Axiovert 200; Carl Zeiss, Inc.) equipped with a 63x NA 1.4 oil immersion objective. Images were obtained using a charge-coupled device (CCD) camera (Hamamatsu Photonics) and analyzed using the MetaMorph image analysis software (MDS Analytical Technologies). Intermediates in platelet release were categorized based on perimeter (proplatelets) or diameter (megakaryocytes, proplatelets, and platelets) using the MetaMorph software, thresholding, integrated morphometry analysis, and software calipers tool. Experiments represent one standard deviation about the mean for at least seven independent cultures.

EM

Released proplatelet-enriched cultures in suspension were fixed with 1.25% paraformaldehyde, 0.03% picric acid, and 2.5% glutaraldehyde in 0.1 M cacodylate buffer, pH 7.4, for 1 h, postfixed with 1% osmium tetroxide, dehydrated through a series of alcohols, infiltrated with propylene oxide, and embedded in epoxy resin. Ultrathin sections were stained and examined with an electron microscope (G2 Spirit BioTwin; Tecnai) at an accelerating voltage of 80 kV. Images were recorded with a CCD camera (2K; Advanced Microscopy Techniques) using digital acquisition and analysis software (Advanced Microscopy Techniques). Rapid-freeze EM samples were prepared as previously described (Italiano et al., 1999). Tantalum tungsten and carbon replicas were picked up on carbon formvar–coated copper grids and examined.

Flow cytometry

Released proplatelet fractions were isolated and cultured as described in “Isolation of released proplatelets/preplatelets” and sampled daily over a period of 5 d. Platelet counts were determined by flow cytometric analysis with a primary rat IgG antibody specific for mouse GPIX (provided by B. Nieswandt, University of Wurzburg, Wurzburg, Germany) and a secondary goat anti–rat antibody conjugated to Alexa Fluor 488 (Invitrogen). Secondary antibody specificity controls were performed. Gates were set using 0.5–10-µm microspheres (Spherotech) and confirmed by DIC microscopy at 63x and 100x. Platelets were isolated from culture intermediates by altering the characteristic forward and side scattering as they passed through the flow cytometer, and their total fluorescence intensity was calculated after subtraction of the secondary specificity control. Platelet counts were based on GPIX-positive objects 0.5–2.0 µm in size and normalized to proplatelet (GPIX positive, 3.3–10-µm particle) counts at 0 d after proplatelet-enrichment. Analysis of platelet counts were performed for at least 15 different cultures. Data were subject to one-way ANOVA for four independent samples and Tukey HSD analysis. Experiments represent one standard deviation about the mean for at least three independent samples.

Released proplatelet transfusion

For proplatelet transfusion and platelet production/survival experiments, cultured released proplatelets and wild-type whole blood platelets were labeled with 5 µM CMFDA (Invitrogen) for 45 min at 37°C (Hoffmeister et al., 2003a,b; Josefsson et al., 2005) Unincorporated dye was removed by centrifugation, and (cultured) released proplatelets or (whole blood) platelets were resuspended in 300 µl of culture media or platelet buffer, respectively. CFDA-labeled proplatelets or control platelets were injected into syngeneic CD61 mice via retro-orbital vein. For recovery and survival determination, blood samples were collected immediately (<2 min) and 1, 2, 4, 6, 24, 48, and 72 h after transfusion into 0.2 ml Aster-Jandl anti-coagulant. Whole blood FPR analysis using flow cytometry was performed, and the percentage of CMFDA-positive platelets was determined (Baker et al., 1997; Hoffmeister et al., 2003a). A total of 200,000 events were collected in each sample. CMFDA-positive platelet counts were normalized to the <2-min
time point (100%), and analyses of platelet counts were performed for at least three different transfusion events. Recoveries from CMFDA-labeled platelet and proplatelet transfusions were ≥1%, and the percentage of circulating labeled platelets, determined at <2 min, was ≥0.1%.

**DIC live cell microscopy**
Isolated proplatelets were diluted in a semisolid medium (60% Leibowitz L-15 medium and 40% DME with 10% fetal bovine serum, 50 μl/1 ml penicillin, and 50 μg/ml streptomycin) in chambers formed by mounting a glass coverslip coated with 3% BSA onto a 10-mm petri dish with a 1-cm hole. Preparations were maintained at 37°C and examined on an inverted microscope (Axiovert 200) equipped with a 63x NA 1.4 objective, an X1.3 incubation chamber, and a 100-W mercury lamp (Carl Zeiss, Inc.). Images were obtained using a CCD camera (Hamamatsu Photonics), and frames were captured at 30-s intervals. Videos 1–4 were generated using the MetaMorph image analysis program.

**Stabilization/depolymerization of released proplatelet microtubule cytoskeletons**
Released proplatelet cultures were incubated at (a) 37°C (normal control) or 4°C for 1 h and again at 37°C for 1 h or (b) in the presence of 5 μM taxol or 5 μM nocodazole for 1 h at 37°C. Samples were centrifuged on poly-lysine–coated glass coverslips and probed with a rabbit polyclonal antibody against dyetyrosinated tubulin then analyzed by immunofluorescence microscopy for different-sized objects. All values were normalized to the 37°C (normal) controls, and experiments were performed in triplicate. Box and whisker plots illustrate sample minimum, lower quartile, median, upper quartile, and sample mean for samples cultured at 4°C. Data were subject to one-way ANOVA for three independent samples and HSD analysis.

**Expression of GFP–α-tubulin and EB3-GFP constructs**
GFP–α-tubulin was cloned into pWZL plasmids containing the sequence for enhanced GFP using previously described methods (Schulze et al., 2004). The released proplatelet fraction was isolated from megakaryocytes that were retrovirally infected to express GFP–α-tubulin and analyzed by fluorescence time-lapse microscopy. Semliki Forest virus–mediated gene delivery was used to express EB3-GFP in mouse megakaryocytes (Patel-Hett et al., 2008). Cultured megakaryocytes were infected by the addition of 1 μl Semliki Forest virus infectious replicons to 400 μl day 2.5 cultures. EB3-GFP movements were visualized by fluorescence microscopy 8–48 h after infection.

**Live cell imaging of GFP–α-tubulin, EB3-GFP, and α-granule movements**
Infected megakaryocytes were transferred onto video chambers maintained at 37°C. Cells were viewed on a microscope (Axiovert 200) equipped with a 63x oil immersion objective, and images were obtained using a CCD camera (Hamamatsu Photonics). Videos 1–4 were prepared using MetaMorph. Pictures of EB3-GFP–α-tubulin were captured at 30, 45-, or 60-s intervals over a course of 4 min. Pictures of EB3-GFP–expressing proplatelets were acquired every 2–5 s with a mean image capture time of 500 ms. The velocity of EB3-GFP comets was determined by dividing the distances traveled by the time elapsed. We included only comets that could be followed for a minimum of 15 s. To visualize α-granules, isolated megakaryocytes (day 4 in culture) were incubated overnight with 150 μg/ml Oregon green 488 human fibrinogen conjugate (Invitrogen) and 100 U/ml Hirudin from leeches (Sigma-Aldrich) in DME [Harrison et al., 1989]. Megakaryocytes were then washed by albumin gradient sedimentation, and the resuspended pellet was placed in a video chamber. Images were acquired at 1-min intervals over a course of 36 min.

**Released proplatelets cultured under continuous shear**
Released proplatelets isolated from fetal liver–derived megakaryocytes were cultured at 37°C for up to 2 h in an incubator shaker (C24KC; New Brunswick Scientific) at 150 rpm, and shear forces were estimated to reach ~0.5 Pa maximally. Sample aliquots were collected every 20 min, and proplatelet counts were determined by flow cytometric analysis. Samples were then fixed, centrifuged, and probed with a rabbit polyclonal antibody against the C-terminal sequence of mouse α-tubulin. Images were acquired using a confocal microscope (TCS SP5; Leica) equipped with a programmable xyz stage using a 20x 0.40 NA dry objective. Quantitative analysis was performed in MATLAB (The MathWorks, Inc.) and Image (National Institutes of Health) using anchor-coded software. Objects were categorized based on area measurements and normalized to initial (time 0) object counts.

**Preparation of photomicrographs**
The digital images produced in MetaMorph were assembled into composite images using ImageJ and Photoshop (CS3; Adobe). Dividing lines explicitly separate different images or separate regions of the same image. No specific features within an image were enhanced, obscured, moved, removed, or introduced, and adjustments made to the brightness, contrast, and color balance were linearly applied to the whole image.

**Online supplemental material**
Fig. S1 illustrates the isolation of specific stages of megakaryocyte development and platelet production. Fig. S2 shows the quantification of platelet release during cell culture. Fig. S3 shows EB3-GFP movements in a released barbell proplatelet. Fig. S4 demonstrates the quantitation of cultured proplatelets by immunofluorescence microscopy. Fig. S5 shows multivesicular bodies present in human proplatelets. Video 1 shows microtubule dynamics during the conversion preplatelets into barbell proplatelets. Video 2 shows α-granule sorting during proplatelet to proplatelet interconversion. Video 3 shows α-granules sorting between the platelet-sized ends of a barbell proplatelet. Video 4 shows EB3-GFP movements in a released barbell proplatelet. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.201006102/DC1.

A. Eftichiev gratefully acknowledges support from Thomas Stossel. This work was supported in part by the National Institutes of Health (grant H568130 to J.E. Ittmano and training grant HL007680 to A. Eftichiev), the National Institute of Dental and Craniofacial Research (shortterm research training grant DE07268 to A. Montalvo), and the American Society of Hematology (2003 Trainee Award to A. Montalvo). We gratefully acknowledge D.A. Wieland and the Harvard Materials Research and Engineering Center (DMR0213805) for confocal imaging. J.E. Ittmano is an American Society of Hematology Junior Faculty Scholar.

Submitted: 16 June 2010
Accepted: 18 October 2010

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