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Brief Report

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Infusion of mature megakaryocytes into mice yields functional platelets

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Thrombopoiesis, the process by which circulating platelets arise from megakaryocytes, remains incompletely understood. Prior studies suggest that megakaryocytes shed platelets in the pulmonary vasculature. To better understand thrombopoiesis and to develop a potential platelet transfusion strategy that is not dependent upon donors, of which there remains a shortage, we examined whether megakaryocytes infused into mice shed platelets. Infused megakaryocytes led to clinically relevant increases in platelet numbers. The released platelets were normal in size, displayed appropriate surface markers, and had a near-normal circulating half-life. The functionality of the donor-derived platelets was also demonstrated in vivo. The infused megakaryocytes mostly localized to the pulmonary vasculature, where they appeared to shed platelets. These data suggest that it may be unnecessary to generate platelets from ex vivo grown megakaryocytes to achieve clinically relevant increases in platelet numbers.

Introduction

While the number of platelet donors is increasing, there is still a significant donor shortage due to the growing population of patients with serious illnesses associated with thrombocytopenia and hemorrhage (1). The use of donor-derived platelets raises the following concerns: variability of quality and quantity, risk of infectious transmission, short lifespan of stored platelets, bacterial contamination during storage, and development of alloantibodies in multi-transfused patients. These problems highlight a need for new strategies to generate platelets for infusion therapy.

Thrombopoiesis, the process by which circulating platelets arise from megakaryocytes remains incompletely understood. In vitro studies suggest that platelets form nodes at tips of proplatelet strands (2). However, direct visualization of live calvaria marrow using multiphoton intravital microscopy suggests that megakaryocytes release large cytoplasmic fragments into the vasculature (3), which must then undergo reorganization into platelets. Studies based on morphologic analysis and quantification of megakaryocyte-like polyploid nuclei in the pulmonary venous system suggested that megakaryocytes release platelets in the lungs (4). Derivation of platelets from megakaryocytes in culture was first reported in 1995 (5) but has been difficult to quantitatively upscale. To date, the best published result from infused in vitro produced platelets used irradiated mice with low platelet counts ($\sim 10^4/\mu\text{l}$) (6). Peak percent donor platelet counts were still only 1%–2%. Given the limited success by which platelets have been generated ex vivo, we examined whether infused megakaryocytes release platelets in vivo. We found that by infusing ex vivo generated murine megakaryocytes into mice, we can achieve an approximately 100-fold increase in recipient platelet count over prior published results, achieving clinically relevant levels of donor platelets. These platelets have a slightly shorter

half-life than infused platelets, but are normal in size, expression of surface markers, and functionality. Infused megakaryocytes appear to be trapped in the pulmonary bed, where they shed their cytoplasm.

Results and Discussion

To address whether infused megakaryocytes give rise to circulating platelets, we generated fetal liver- (FL-) and BM-derived megakaryocytes (Supplemental Figure 1; supplemental material available online with this article; doi:10.1172/JCI43326DS1) (7). Mature megakaryocytes were separated from other cells and proplatelets using a 2-step density gradient to produce “large cells,” with more than half possessing a diameter greater than 50 μm and with only approximately 2.5:1 proplatelets/cell (Figure 1A). The remaining “small cells” had approximately 10:1 proplatelets/cell (Figure 1A). Ploidy analysis showed FL small cells with low DNA ploidy relative to FL large cells (Figure 1B).

Positive control WT platelets were isolated and infused into αIIb^+ recipient mice, with only human αIIb on their platelet surface (8), to allow flow cytometric detection of infused platelets using species-specific anti- αIIb (CD41) Abs. After infusion, WT platelets were detected in αIIb^+ recipient mice immediately (i.e., 5-minute time point), with an overall half-life of approximately 36 hours (Figure 1, C, E, and F). In contrast, infused FL large cells resulted in delayed platelets, with a peak at approximately 90 minutes (Figure 1, D and E). These platelets had a shorter overall half-life of approximately 20 hours. Based on the number of cells infused, the peak increase in platelet count, and the recipient mouse blood volume of approximately 2 ml, we calculated 100–200 platelets from each large cell, assuming all cells gave rise to platelets. Infused FL small cells enriched with proplatelets gave rise to an immediate peak similar to infused WT platelets; however, these platelets had a truncated half-life of approximately 2 hours (Figure 1E). Infusing adult BM megakaryocytes resulted in a similarly delayed appearance of platelets as with FL-derived megakaryocytes, but with a slightly longer half-life of 24 hours

Conflict of interest: The authors have declared that no conflict of interest exists.

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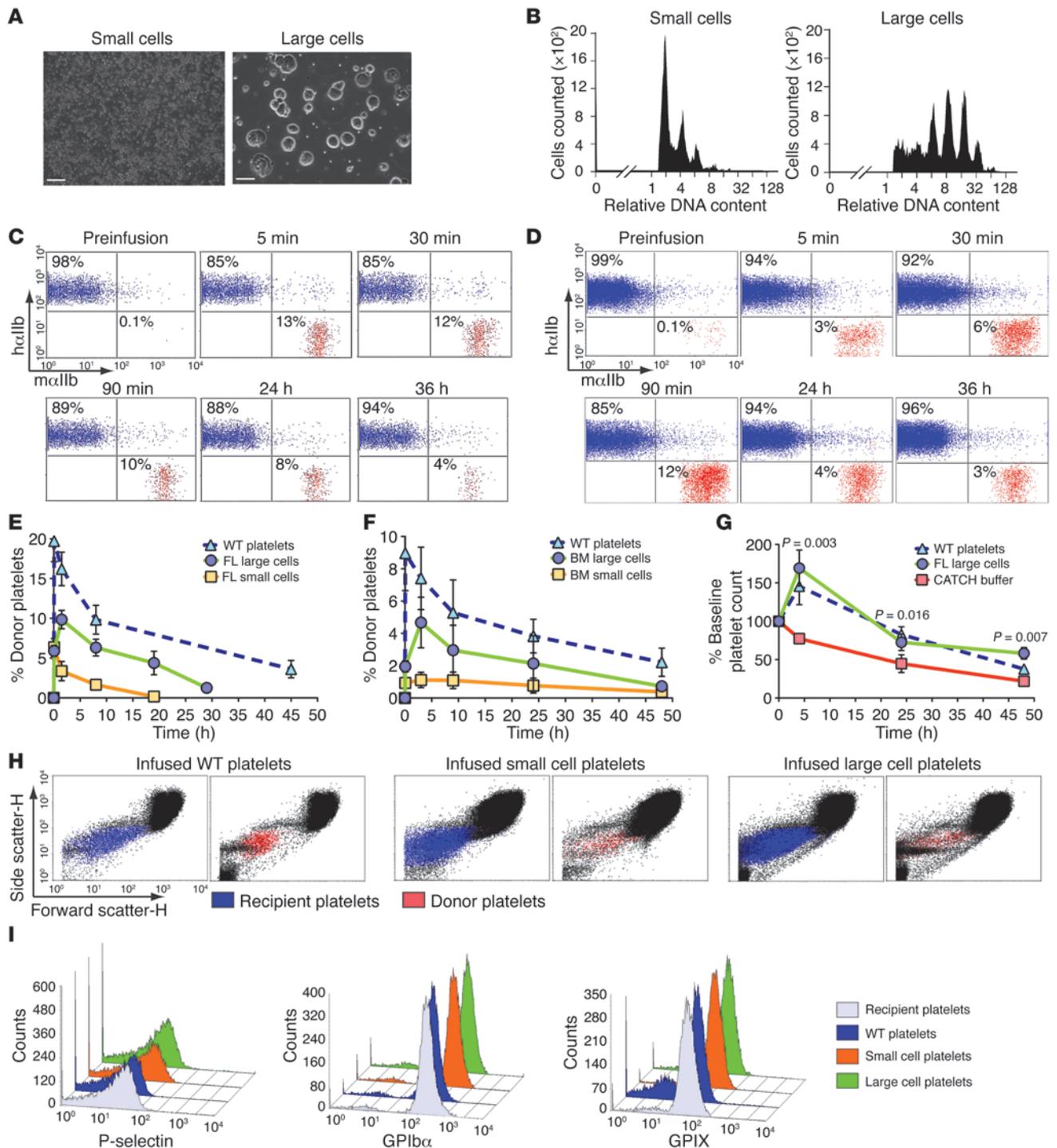
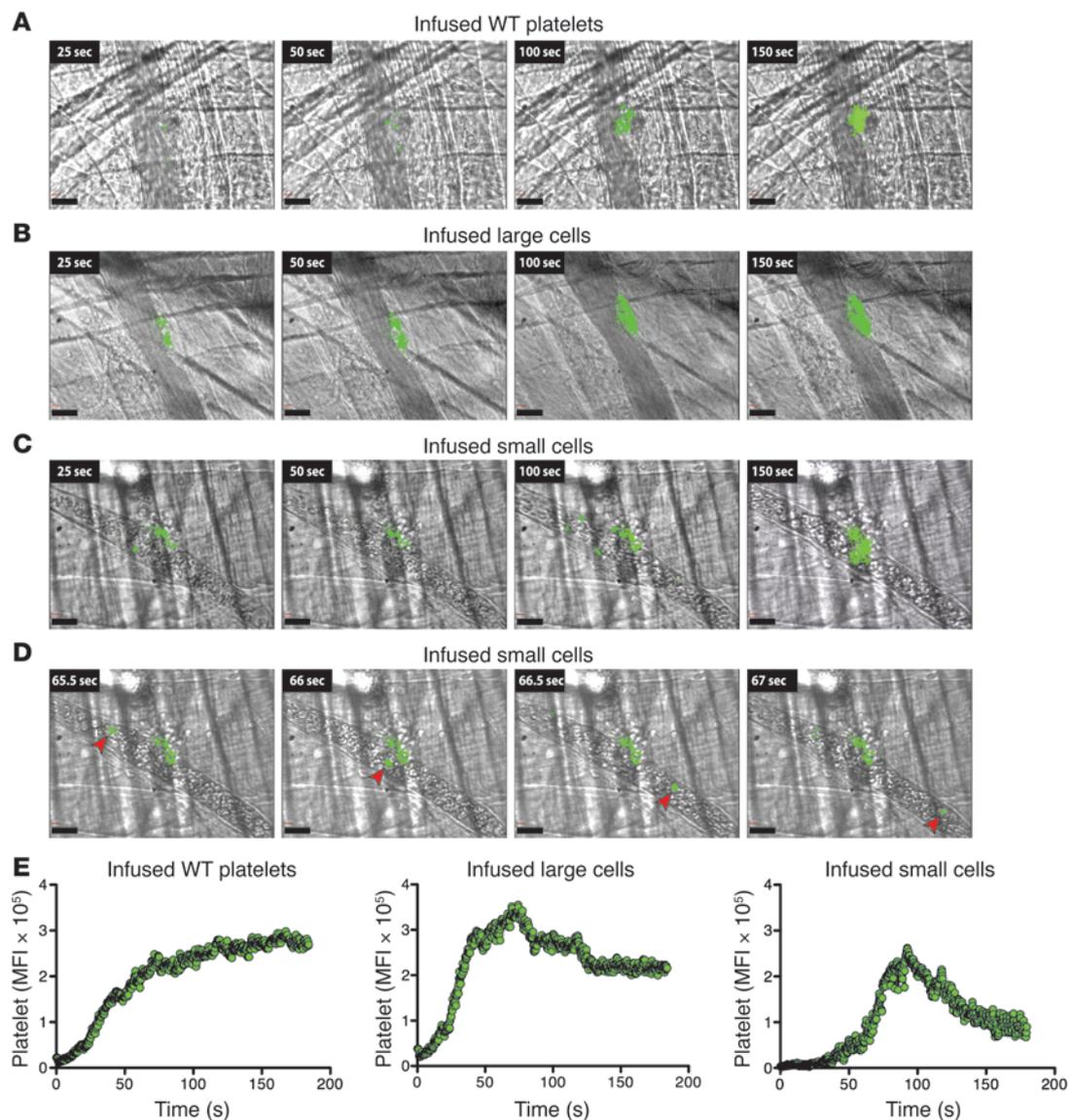


Figure 1

Characterization and infusion of megakaryocytes. (A) Representative fields of small and large cells. Scale bars: 100 μ m. (B) Representative analysis of DNA content of FL small and large cells. (C) Flow cytometry from recipient mouse before and after infusion of 10^8 WT platelets or (D) 10^6 FL large cells. (E) Flow cytometric percentage of 10^6 infused FL large cells and (F) 10^6 infused adult BM cells. $n = 5$ for WT platelets, $n = 9$ for FL cells, $n = 5$ for BM studies. (G) Percent platelet rise in irradiated thrombocytopenic mice after infusion. $n = 5$ per arm. Mean \pm 1 SD are shown. Initial platelet counts (10^8 /ml) in the 3 groups were: CATCH buffer, 1.8 ± 0.2 ; platelets, 1.9 ± 0.3 ; large cells, 1.0 ± 0.2 . (H) Size determination of circulating recipient (blue) and infused platelets (red) by forward versus side scatter analysis. (I) Representative flow cytometric analysis of infused and FL-derived platelets comparing P-selectin, GPIb α , and GPIX.

**Figure 2**

Platelet incorporation into arterial clots after laser injury. (A–C) Representative images of platelets incorporating into clots after infusion of platelets or indicated cells. (A) Donor WT platelets detected using a labeled anti–mouse α IIb Ab. (B and C) Same as in A, but after infusion of FL cells. (D) Sequential stills from left to right noting a recirculating mouse α IIb⁺ cell (arrowheads) after small cell infusion. Scale bars: 30 μ m. (E) Summation of donor platelets incorporated into growing thrombi after infusion of either WT platelets or FL cells. Twenty movies were evaluated per graph.

(Figure 1F). To simulate clinical thrombocytopenia, we irradiated mice and infused CATCH buffer (1 \times PBS, 1.5% BSA, 1 mM adenosine, 2 mM theophylline, and 0.38% sodium citrate), WT platelets, or FL large cells near the induced platelet nadir and observed that both platelets and megakaryocytes significantly increased the platelet count relative to CATCH buffer over a time course of more than 24 hours (Figure 1G).

To understand the shortened half-life of platelets derived from infused large cells, we examined their size distribution and microparticles compared with infused WT platelets and found no differences (Figure 1H). Another indicator of platelet activation is the expression of surface P-selectin (9). Flow cytometric analysis showed that surface P-selectin levels were similar in platelets derived from infused FL cells and infused WT platelets (Figure 1I).

ADAM17 is a metalloproteinase found in cultures that shortens platelet half-life (10) and cleaves the glycosialin extracellular portion of GPIb α , inactivating the GPIb/IX receptor without altering receptor density (11). Platelets derived from infused FL cells and infused WT platelets displayed similar ratios of extracellular GPIb to GPIX (Figure 1I). Thus, the slightly shortened half-life of the platelets derived from infused large cells does not appear to be due to ADAM17 activity.

Clinically, platelets are transfused not to increase platelet number, but to reverse or prevent a bleeding diathesis due to thrombocytopenia. In the laser-induced cremaster arteriole injury model, we looked at incorporation of infused WT platelets and platelets derived from infused FL cells into growing clots. In all settings, the platelets readily become incorporated into the developing



Table 1
Effects of infused large cells in the FeCl₃ thrombosis model

Donor	Time to occlusion (min)	Initial occlusion (%)	Occluded at 30 min (%)	Blood flow (ml/min)
Buffer	7.4 ± 0.9	5/5 (100%)	5/5 (100%)	4.2 ± 1
WT large cells	5.3 ± 0.5 ^A	5/5 (100%)	5/5 (100%)	3.3 ± 1 ^A
mUK large cells	>30	0/5 ^A	0/5 ^A	15.7 ± 1 ^A

^A*P* < 0.03 compared with CATCH buffer infusion.

thrombi. WT platelets and platelets derived from FL large cells were similarly incorporated (Figure 2, A and B). Platelets derived from FL small cells incorporated to a lesser extent, with a distinct population of CD41⁺ cells that recirculated and rarely incorporated into the clot (Figure 2, C and D, and Supplemental Video 1). This phenomenon was rarely seen after infusion of FL large cells (Figure 2B and Supplemental Video 2), and never with infused WT platelets (Figure 2A and Supplemental Video 3).

We also examined platelet function using an FeCl₃ carotid artery injury model after infusing either CATCH buffer or FL large cells into the α IIb⁺ recipient mice, which have a mild bleeding diathesis likely because of low CD41 surface density (12). Infusion of FL large cells significantly shortened time to development of stable occlusion (Table 1). We also infused FL large cells from mUK mice, which ectopically express and store urokinase in their α -granules (13) and are resistant to thrombosis in the FeCl₃ carotid artery injury model. Transfusion of mUK platelets into WT mice blocked clot development (14). We reasoned that if infused mUK platelets from FL large cells are functional, they would interfere with clotting in the α IIb⁺ recipient mice. Indeed, infused mUK large cells failed to form stable occlusions (Table 1).

To begin to address where infused megakaryocytes shed platelets, we labeled megakaryocyte nuclei with BrdU. Various organs were isolated up to 36 hours after infusion. Virtually all of the BrdU-stained nuclei were in the lungs (Figure 3A). Stained nuclei were visible for up to 24 hours (Figure 3B and data not shown). A few nuclei were visible in the red pulp of the spleen (Figure 3C). None were present in the liver, heart, brain, or BM (data not shown). The BrdU-labeled large cells appear to retain their cytoplasm for up to 30 minutes after infusion in pulmonary microvessels (Figure 3, B and D), consistent with the delay in peak platelet count after infusion of FL large cells. To confirm this observation, we stained the tissues with an anti-murine CD41 Ab and detected positively stained cytoplasm up to 30 minutes (Figure 3D).

Our studies and prior histological studies (4) suggest that platelets can be released from circulating, mature, high-ploidy megakaryocytes directly within the vascular bed. Given the recent study showing megakaryocytes shedding large cytoplasmic fragments at the vascular niche in the marrow (3), we propose that both large cytoplasmic fragments and whole megakaryocytes may escape into the vascular system and shed platelets within the pulmonary bed using mechanisms consistent with those revealed by in vitro studies (2), but with concurrent flow and local vascular factors involved as well (15).

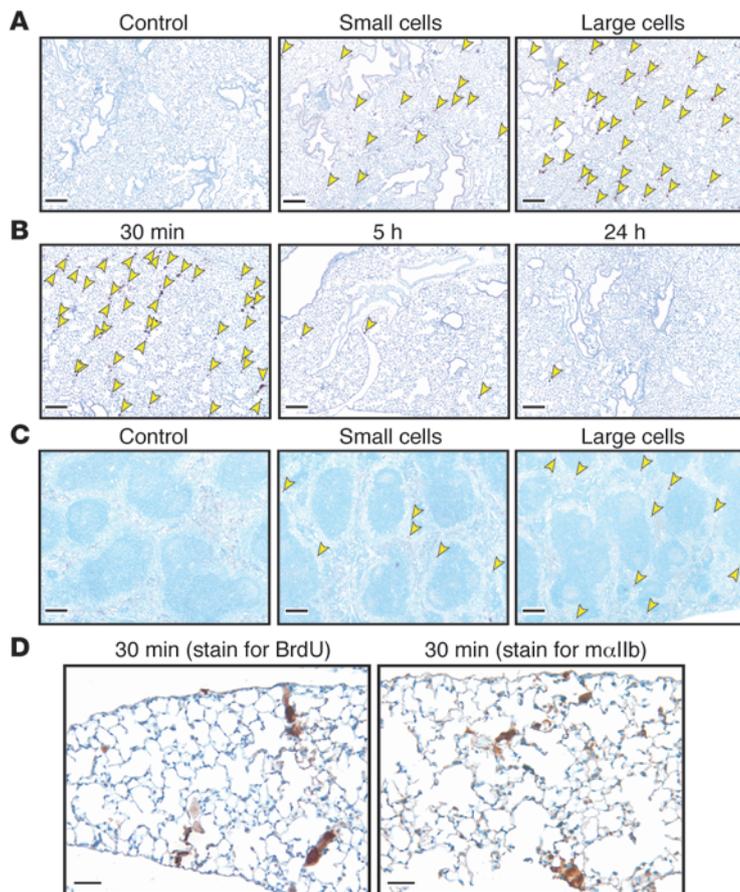
One would expect that megakaryocytes lodging in the lungs might pose a cardiovascular challenge. However, based on calculations shown in Supplemental Table 1, we only blocked 0.4%–1.7%

of the entire alveolar capillary bed. In addition to the capacity of the pulmonary vasculature to handle an influx of megakaryocytes, another question is whether this bed is specialized for platelet release. Individuals with significant right to left cardiovascular shunts are known to have lower platelet counts, which others have proposed to result from pulmonary bypass by circulating megakaryocytes (16). However, in fetal circulation, where one naturally bypasses the pulmonary bed, platelets are present (17).

We have shown that derived platelets from infused megakaryocytes are normal in size and expression of surface receptors and can be incorporated into growing thrombi; however, why these platelets have a shorter half-life than infused platelets is unclear. We anticipated that newly generated platelets would have a prolonged half-life. Whether the shortened half-life is due to in vitro culture conditions is unknown. Previously, it had been suggested that ADAM17 is present in the media and shortens ex vivo generated platelet half-life (6). Our studies showed no change in derived platelet half-life after megakaryocytes were grown in the presence of two inhibitors of ADAM17, GM6001 and TAP-1 (Supplemental Figure 2, A and B). An alternative explanation for the shortened half-life is that most of our studies were performed with FL megakaryocytes, and fetal platelets have a shorter half-life compared with adult platelets (18). However, cultured infused adult BM megakaryocytes produced a similar delay in appearance and short half-life (Figure 1F). Whether culture conditions affects half-life could not be tested, as there are insufficient primary megakaryocytes in isolated marrow to test this possibility.

In vitro generation of a large number of biologically responsive platelets has remained problematic. Our studies open the possibility of establishing a human cell line that can be expanded and differentiated into megakaryocytes, leading to a non-donor-dependent source of platelets. Such a line exists from mice: G1ME cells, which are derived from GATA-1-deficient embryonic stem cells and form approximately 50% megakaryocytes after reexpression of GATA-1 (19). Modification of such lines to ectopically express a protein of interest during megakaryopoiesis might then be useful for targeted delivery of ectopic protein to sites of injury (20). This additional benefit of generating modified platelets in vivo from infused modified megakaryocytes is supported by studies showing efficacious, targeted urokinase delivery by platelets derived from mUK mouse megakaryocytes (Table 1).

In summary, we have addressed whether infused megakaryocytes can release platelets within the pulmonary bed and demonstrated that biologically active platelets can be formed in vivo with characteristics similar to those of normal platelets. The process is vigorous, and enough platelets are formed so that platelet count can be boosted and hemostasis can be improved and modified by targeted delivery of ectopic proteins. Based on our estimate of 100–200 platelets generated per infused megakaryocyte, the challenge is to

**Figure 3**

Organ distribution studies of infused cells. (A) Staining of lung from $h\alpha IIb^+$ mice infused with saline or small or large cells grown in BrdU (arrows point to stained nuclei). (B) Kinetics of BrdU-labeled large cells in the lungs. (C) Same as in A but for spleen. Scale bars (A–C): 200 μm . (D) Large FL cells 30 minutes after infusion in lungs: BrdU-labeled nuclei (left) and $m\alpha IIb$ (right). Scale bars: 50 μm . Data are representative of 3 separate studies.

generate 10^9 mature megakaryocytes to achieve a 10% rise in platelet count in an average 70-kg patient.

Methods

Characterization of the mice studied. Donor cells and platelets were derived from C57BL/6 WT mice (The Jackson Laboratory) or mUK-transgenic mice, which ectopically express murine urokinase within megakaryocytes (14). Recipient mice were homozygously transgenic for $h\alpha IIb$ and null for the expression of platelet mouse αIIb ($m\alpha IIb^{-/-}$) (8), designated $h\alpha IIb^+$ mice, and expressed 20% of the level of CD41 seen on human platelets (12). All animal studies were done with approval of the Institutional Animal Utilization Committee at the Children's Hospital of Philadelphia.

Isolation of platelets and megakaryocytes ex vivo. FL megakaryocytes were obtained from E14 FL cells homogenized and cultured as previously described (7). Adult BM cells were obtained from femurs and tibiae of C57BL/6 mice (21). Mature megakaryocytes were isolated using a 2-step density gradient (21). Washed platelets derived from the inferior vena cava of C57BL/6 mice in acid-citrate-dextrose were prepared as previously described (22). Platelet counts were determined using a HemaVet counter (Triad Associates). Platelets and/or megakaryocytes were infused into recipient mice retro-orbitally or by tail vein; the two approaches gave similar outcomes (Supplemental Figure 3).

Characterization of the megakaryocytes. Megakaryocytes to proplatelet number was determined visually with a hemocytometer. DNA ploidy was assessed by flow cytometry after staining with propidium iodide using a FACScan (BD) as described previously (23).

Flow cytometric studies in infused $h\alpha IIb^+$ mice. Retro-orbital blood samples from recipient mice were double stained with monoclonal FITC-conjugated mouse anti-human CD41 Ab (eBioscience) and monoclonal phycoerythrin-

conjugated (PE-conjugated) rat anti-mouse CD41 Ab (BD Biosciences) for 30 minutes and analyzed by flow cytometry.

Activation of infused platelets was assessed by 3-color whole blood flow cytometry, using monoclonal mouse anti-human CD41 (PerCP-Cy5.5), PE-rat anti-mouse CD41, and monoclonal FITC-rat anti-mouse P-selectin Abs (all from BD Biosciences). To examine the relative expression of membrane receptors in recipient versus donor platelets, whole blood was stained with mouse anti-human CD41 (PerCP-Cy5.5), PE-rat anti-mouse CD41, and either monoclonal FITC-labeled rat anti-mouse GPIIb α or rat anti-mouse GPIX Ab (Emfret Analytics).

Infusion studies in thrombocytopenic $h\alpha IIb^+$ mice. Mice were subjected to a high dose of irradiation (1,000 centigrays total; two sessions, 24 hours apart). Platelet counts were initially monitored daily to determine a temporal platelet profile. Animals included in these studies had platelet counts between 1×10^8 to 2×10^8 /ml on day 7 after irradiation and immediately before infusion of the cells in 200 μl CATCH buffer. Additional counts were done at 4, 24, and 48 hours after infusion.

Cre master laser injury functional studies. One hour after cell infusion, recipient $h\alpha IIb^+$ male mice were studied in the cremaster laser injury model (24). Anti-mouse CD41 Fab fragments labeled with Alexa Fluor 488 (Pierce Biotechnology) were injected intravenously 5 minutes before injury. Data were collected over a course of 2.5 minutes at 5 frames per second.

FeCl₃ carotid artery injury functional studies. FeCl₃-induced arterial injury was induced in $h\alpha IIb^+$ mice 1 hour after infusion. Studies were done as previously described (20), but the 20% FeCl₃ injury was for 3 minutes. Total flow was recorded for 30 minutes.

Infused megakaryocyte fate studies. FL-derived cells were cultured for 5 days and then exposed to 10 μM BrdU (Sigma-Aldrich) for 48 hours



prior to infusion. Following infusions, recipient mice were sacrificed and organs isolated, then fixed in formalin at predetermined time points. Detection of BrdU-labeled nuclei was performed with a rat polyclonal anti-BrdU Ab and a biotinylated rabbit polyclonal anti-rat IgG as the secondary Ab (Abcam), followed by a DAKO detection kit (EnVision). Megakaryocyte cytoplasm in the lungs was similarly studied using a goat polyclonal Ab against murine α IIB (Santa Cruz Biotechnology Inc.) and a secondary biotinylated rabbit polyclonal anti-goat IgG Ab (Abcam).

Statistics. Differences between groups were compared using 2-tailed Student's *t* test. Statistical analyses were performed using Microsoft Excel. Differences were considered significant when *P* values were 0.05 or less.

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