Turbulence orchestrates actin–mitochondria dynamics to preserve GPIbα and support iPSC-derived platelet biogenesis

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ABSTRACT

In vitro manufacturing of functional platelets remains limited by low yield and poor quality, impeding clinical application. To address this, we developed a turbulence-assisted system using defined physical stimulation to enhance platelet production from immortalized megakaryocyte cell lines (imMKCLs). This approach significantly increases the yield of glycoprotein Ibα (GPIbα)$^{+}$ induced pluripotent stem cell-derived platelets (iPSC-platelets). However, the underlying mechanisms have remained unclear. Here, we show that GPIbα^{+} iPSC-platelets retain high mitochondrial membrane potential, low phosphatidylserine (PS) exposure, and active ATP-dependent flippases, preserving mitochondrial integrity and platelet functionality. In contrast, GPIbα^{-} platelets exhibit PS exposure, ADAM17 activation, and selective GPIbα shedding. Notably, turbulent flow induces late-stage actin depolymerization, promoting even mitochondrial distribution within maturing imMKCLs and enhancing mitochondrial inheritance. These findings uncover a key role of turbulence in regulating actin dynamics and mitochondrial allocation during platelet biogenesis, providing a mechanistic foundation for improving in vitro platelet production for therapeutic use.

INTRODUCTION:

Amid the scarcity of safe and effective therapies for patients with thrombocytopenia or acute bleeding, donor-derived platelet products remain the cornerstone of transfusion medicine. However, these products face significant limitations, including a short shelf life of approximately 4–5 days (Brixner et al., 2024) due to the lack of long-term storage methods that preserve platelet function and morphology, as well as an inconsistent supply that is entirely dependent on donors. A major clinical challenge is platelet transfusion refractoriness (allo-PTR), which arises from alloimmunization due to repeated transfusions or pregnancy (Panch et al., 2023). This condition is primarily driven by sensitization to platelet allo-antigens, such as human leukocyte antigen class I (HLA-I) and human platelet antigen (HPA). Currently, no effective treatments exist when matched donor products for HLA or HPA are unavailable.

In this context, we conducted the first-in-human clinical trial using autologous induced pluripotent stem cell-derived platelets (iPSC-platelets) to treat an allo-PTR patient with anti-HPA-1a antibodies, resulting from an HPA-1b/1b genotype and pregnancy (Sugimoto et al., 2022a). This trial was made possible by the development of immortalized megakaryocyte progenitor cell lines (imMKCLs) capable of generating iPSC-platelets (Nakamura et al., 2014). Following an established protocol for imMKCL generation, we successfully created a master cell bank of imMKCLs, enabling the on-demand production of platelets (Sugimoto et al., 2022b).

Another key breakthrough in platelet biomanufacturing was the development of an efficient, large-scale production system. A pivotal innovation in this field involved identifying a novel mechanobiological concept: turbulent flow synergizes with shear stress to promote megakaryocyte maturation and functional platelet biogenesis. This was inspired by *in vivo* observations where physical stress—generated by blood flow—enhanced platelet formation, a phenomenon that was subsequently recapitulated *in vitro*.

In vivo, multiple mechanisms of thrombopoiesis have been proposed, including proplatelet extension, cytoplasmic rupture, fragmentation, and membrane budding at the bone marrow sinusoid interface (Nishimura et al., 2015; Tilburg et al., 2022; Potts et al., 2020). Moreover, recent discoveries have identified the lung vasculature, especially at vessel bifurcations, as a significant site of platelet generation (Lefrançais et al., 2017; Zhao et al., 2023). These bifurcations induce turbulent flow, which can be mimicked in vitro using platforms like the VerMES reactor or even in simple flask cultures. Under such conditions, the number of GPIbα$^+$ platelets markedly increases (Ito et al., 2018; Okamoto et al., 2024). However, the precise molecular mechanisms by which turbulence enhances GPIbα$^+$ platelet production remain poorly understood, limiting efforts to fully optimize *in vitro* systems.

Mitochondria are essential for platelet function, primarily by generating ATP to support platelet activation and aggregation (Melchinger et al., 2019). They also regulate reactive oxygen species (ROS) levels and calcium homeostasis—both of which are critical for platelet activity (Chen et al., 2013; Kholmukhamedov et al., 2018; Ajanel et al., 2023). Mitochondrial dysfunction impairs platelet responses (Richman et al., 2023; Ding et al., 2023) and has been associated with various pathological conditions, including Parkinson's disease, Alzheimer's disease, and type 2 diabetes (Shi et al., 2008; Avila et al., 2012; Zharikov and Shiva, 2013; Antony et al., 2015; Wang et al., 2017; Twomey et al., 2018; Melchinger et al., 2019). These findings underscore the critical role of mitochondria in maintaining normal platelet function. However, our understanding of mitochondrial dynamics during platelet production remains limited. In particular, how mitochondria are evenly distributed within platelets during their biogenesis has not been investigated.

In this study, we identified that functional platelet production was significantly increased under turbulent stress. Specifically, GPIbα$^+$ iPSC-platelets generated under turbulent conditions show elevated mitochondrial membrane potential and reduced phosphatidylserine (PS) exposure,

indicating preserved mitochondrial function. In contrast, GPIbα⁻ iPSC-platelets, lacking sufficient ATP to fuel flippases, display increased PS exposure and undergo ADAM17-dependent GPIbα shedding. Furthermore, turbulence promotes balanced F-actin dynamics in megakaryocytes, supporting even mitochondrial distribution and facilitating efficient platelet biogenesis. These findings underscore the critical role of turbulence in orchestrating intracellular cytoskeletal remodeling and mitochondrial integrity, offering key insights into improving both the quality and yield of *in vitro* platelet production systems.

RESULTS:

Turbulence increases high-quality iPSC-platelet production indicated by increased GPIbα expression and mitochondria membrane potential.

To determine whether varying levels of turbulent energy and shear stress influence GPIbα positivity, we compared iPSC-platelet production from Clone 17 imMKCLs in different conditions: static culture (dish), orbital shaking flask (sub-optimal shear and turbulence), and the VerMES™ bioreactor (optimal shear and turbulence) (Ito et al., 2018) (Fig. 1 A; Fig. S1 A). By analyzing surface markers such as integrin alpha 2b (CD41) and GPIbα, we found that turbulence not only increases the functional iPSC-platelets yield but also improves the proportion of functional iPSC-platelets (Fig. 1, B–D). Only GPIbα^{+} iPSC-platelets were activated by ADP/Trap6, or PMA stimulation (Fig. S1 B), and they were fluorescent upon Calcein-AM incubation (Fig. 1 E). Interestingly, GPIbα^{+} iPSC-platelets showed higher mitochondria membrane potential (MMP), as revealed by MitoTracker Deep Red staining, compared to GPIbα^{-} iPSC-platelets (Fig. 1 F). Additionally, a culture swap experiment (dish to flask, flask to dish on day 4) revealed that turbulence from day 4 onward, corresponding to the stage of platelet release (Fig. S1, E and F), is essential for improved iPSC-platelets yield, aligned with the onset of iPSC-platelets production (Fig. 1, G and H), suggesting a positive relationship between mitochondria inclusion and GPIbα expression that is promoted by turbulence after day 4.

Mitochondria activity regulates GPIbα expression.

Next, we investigated whether mitochondria play a positive regulatory role in GPIbα expression. We compared MMP, reactive oxygen species (ROS) levels, and ATP levels in GPIbα^{+} versus GPIbα^{-} iPSC-platelets and found that GPIbα^{+} iPSC-platelets exhibited higher

levels across all three parameters (Fig. 2 A). Furthermore, MMP was inversely correlated with phosphatidylserine (PS) exposure, measured by Annexin V binding, a marker of apoptosis (Fig. 2 B). These findings were consistent in the produced iPSC-platelets from imMKCLs transfected with CoralHue® mito-mAG vector, which allowed visualization of the reduced presence of intact mitochondria in static iPSC-platelets compared to those cultured in flasks (Fig. 2 C; Fig. S2 A).

To further investigate the role of mitochondria in GPIbα expression, we inhibited mitochondrial activity using FCCP (carbonyl cyanide-p-trifluoromethoxyphenylhydrazone), a well-known uncoupler of proton-mediated ATP production in mitochondria. This treatment led to a decrease in GPIbα expression, which was reversed when iPSC-platelets were pre-treated with ADAM17 inhibitors such as KP457 (Hirata et al., 2017), high concentration of GI254023X (Metz et al., 2012), TAPI-1 (Nishikii et al., 2008), and GM6001 (Bergmeier et al., 2004) (Fig. 2 D). These results were also observed in donor-derived human platelets (Fig. S2 F).

Additionally, in order to confirm whether the MMP levels is dependent on the GPIb-X-IX complex, we used GPIX- knockout (KO) imMKCLs, which predominantly produce GPIbα^{-} iPSC-platelets. However, no significant difference in MMP was observed between these and control cells (Fig. 2, E and F), confirming that mitochondria is a positive upstream regulator of GPIbα.

Mitochondria supply flippases with ATP to maintain GPIbα expression.

It has been previously reported that flippases mediate PS exposure, which in turn activates ADAM17 (Sommer et al., 2016), and that scramblases, such as TMEM16F (Fujii et al., 2015), become active during platelet functional decline. To determine whether mitochondrial regulation of GPIbα expression involves these factors, we examined PS and

phosphatidylcholine (PC) dynamics in iPSC-platelets. We used fluorescent PS (NBD-PS) and PC (NBD-PC), which are internalized by recipient platelets if flippases or scramblases are active, respectively (Fig. 3 A). Consistent with our earlier findings in Annexin V binding assay (Fig. S1 C), NBD-PS was internalized by GPIbα^{+} but not GPIbα^{-} iPSC-platelets (Fig. 3 B; Fig. S3 A). When ionomycin was added, a significant increase in calcium levels and a subsequent decrease in ATP levels were observed, leading to reduced GPIbα expression and diminished NBD-PS internalization (Fig. 3 C and D; Fig. S3 A). These results indicate that mitochondrial ATP production fuels flippases, internalizing PS and maintaining inactive conformation of ADAM17, preventing GPIba shedding in iPSC-platelets.

Turbulence imMKCLs exhibit uniform mitochondria distribution

Next, we investigated intracellular differences between maturing dish and flask imMKCLs, as mouse and human platelets inherit their mitochondria from megakaryocytes (Richardson et al., 2005; Jacob et al., 2024). After staining of mitochondria by MitoTracker Deep Red and of F-actin by SPY555-FastAct, a F-actin-stabilizing jasplakinolide derivative, respectively, confocal imaging revealed uniform distribution of mitochondria and F-actin in flask imMKCLs, while dish imMKCLs displayed distinct megakaryocyte polarization. However, no differences were observed in the surface expression of CD41/GPIbα or mitochondrial membrane potential (MMP) over the 6-day culture period (Fig. 4, A and B; Fig. S4, A and B). When mitochondrial distribution was disrupted using Mdivi-1, there was a dose-dependent shift toward the production of primarily GPIbα^{-} iPSC-platelets (Fig. 4 C). No significant differences were observed in the oxygen consumption rate between day 4 dish or flask imMKCLs, and MMP differences were only seen in iPSC-platelets (Fig. 4, D and E) These results suggest that turbulence promotes uniform mitochondria distribution in megakaryocytes leading to efficient mitochondria inclusion by platelets.

Turbulence regulates actin dynamics to produce high-quality platelets.

The actin cytoskeleton is known to play a crucial role in mitochondrial distribution during cell division (Moore et al., 2021). To determine whether actin contributes to the uniform distribution of mitochondria in imMKCLs, we examined cytoskeletal dynamics under different culture conditions. Interestingly, there were no significant differences in the expression of cytoskeleton-related genes (Fig. 5, A–C) or total actin protein levels (Fig. 5, D and E) between dish and flask cultures. However, from day 4 onwards, we observed a marked, turbulence-dependent reduction in F-actin-specific signals in turbulent cultures compared to static dish cultures (Fig. 5 F).

To explore how reduced F-actin levels by the SPY555-FastAct staining —at least as experimentally detectable—might facilitate mitochondrial delivery, we first investigated the effects of Latrunculin A, a monomeric actin-binding molecule that prevents actin polymerization. Treatment with Latrunculin A resulted in a dose-dependent decrease in both GPIbα expression and mitochondrial membrane potential (MMP), accompanied by increased Annexin V binding as well as decreased F-actin levels in imMKCLs (Fig. 5, G and K). Conversely, treatment with Cytochalasin D, which protects actin filament barbed ends, but not pointed ends, from actin polymerization, significantly enhanced F-actin levels as indicated in imMKCLs but still led to diminished GPIbα expression in iPSC-platelets (Fig. 5, H and L). These results suggest that an intermediate, dynamically relaxed actin structure—characterized by moderate F-actin levels (Fig. 5 F)—may be optimal for functional platelet production.

To further assess whether actin polymerization-depolymerization dynamics influence GPIbα expression in iPSC-platelets, we evaluated the roles of cofilin, a key mediator of actin depolymerization, and the Arp2/3 complex, a regulator of actin branching (reference). Inhibition of cofilin using SZ-3, or the Arp2/3 complex using CK-666, also resulted in reduced GPIbα

expression (Fig. 5, I and J) , further supporting the importance of actin dynamics in the platelet formation.

Collectively, these findings highlight the pivotal role of turbulence in modulating actin dynamics and mitochondrial distribution, both of which are essential for the generation of functional iPSC-derived platelets. We therefore propose that the dynamic turnover of actin filaments—through a process of balanced polymerization and depolymerization, known as treadmilling—represents a critical mechanism for enabling complete mitochondrial delivery and efficient iPSC-platelet production (Fig. 5 K).

DISCUSSION:

In this study, we sought to elucidate the underlying mechanisms by which turbulent flow facilitates the generation of GPIbα^{+} iPSC-derived platelets (iPSC-platelets) from imMKCLs, as previously described (Ito et al., 2018). To this end, we conducted comparative analyses under turbulent flow and static culture conditions (Fig. 1 A; Fig. S1 A). These experiments revealed that both the proportion and absolute number of GPIbα^{+} iPSC-platelets were significantly increased under turbulent conditions (Fig. 1, B–D). Further characterization confirmed the high quality of these platelets, as demonstrated by assays assessing GPIIb/IIIa activation and P-selectin (CD62P) exposure (Fig. S1 B), Annexin V binding (Fig. S1 C), Calcein-AM retention (Fig. 1 F) (Moreau et al., 2016; Zhao et al., 2023), and uptake of fluorescently labeled Factor V (Fig. S1, J–L) (Sim et al., 2017). Expression levels of GPIbα were correlated with other activation-related markers, such as PAR1 and GPVI (Fig. S1 D). These markers are also known to undergo ADAM-mediated shedding, similar to GPIbα, suggesting that GPIbα^{-} platelets may be more prone to shedding under whole-cell conditions (Ludeman et al., 2004; Gardiner et al., 2007).

Notably, GPIbα^{+} iPSC-platelets retained functional mitochondria, as evidenced by preserved mitochondrial signals, maintained membrane potential, and robust ROS and ATP production (Fig. 1 E, Fig. 2, A and C). Using peripheral blood-derived human platelets, we confirmed that prolonged storage at 22°C or 37°C led to a decline in mitochondrial membrane potential, accompanied by reduced GPIbα expression and increased phosphatidylserine (PS) exposure (Fig. S2, D and E).

These findings suggest that turbulent flow conditions enhance the efficient incorporation of mitochondria into platelet particles. A culture-switch experiment further demonstrated that introducing turbulence from day 4 onward—corresponding to the late maturation stage of imMKCLs—is critical for increasing GPIbα^{+} iPSC-platelet yields (Fig. 1, G and H). This indicates that mitochondrial allocation into platelets is regulated during late-stage megakaryocyte maturation and subsequent platelet release (Fig. S1 F). Concomitantly, we observed a turbulence-specific reduction in F-actin levels from day 4, prompting the hypothesis that turbulence modulates F-actin dynamics to facilitate mitochondrial distribution, a point we explore further below.

Previous reports have shown that GPIbα is subject to ectodomain shedding via ADAM17, reducing its surface expression on both iPSC- and primary-derived platelets (Bergmeier et al., 2004; Nishikii et al., 2008). However, the upstream regulatory mechanisms have remained elusive. In this study, we demonstrate that GPIbα^{+} iPSC-platelets maintain ATP-dependent flippase activity, which actively suppresses PS externalization. In contrast, impaired mitochondrial function leads to PS exposure and subsequent ADAM17-mediated GPIbα shedding. Importantly, scramblase activity was not elevated in GPIbα^{-} iPSC-platelets, suggesting that PS exposure in this population arises solely from diminished flippase activity—a departure from earlier findings implicating Ca^{2+}-dependent scramblase TMEM16F in PS externalization (Fujii et al., 2015). Ionomycin stimulation failed to elicit Ca^{2+} influx in GPIbα^{-}

iPSC-platelets (Fig. 3 D), indicating a deficiency in the calcium influx system, in contrast to intact peripheral platelets. Supporting this, peripheral blood platelets subjected to long-term storage at 22°C exhibited increased scramblase and decreased flippase activity (Fig. S3 B).

While our previous work demonstrated that the ADAM17 inhibitor KP457 enhances the production of GPIbα^{+} iPSC-platelets (Hirata et al., 2017), the current findings suggest that mitochondrial dysfunction is an upstream event that leads to GPIbα shedding. Importantly, GPIbα expression itself did not affect mitochondrial function, as shown in GPIX knockout (KO) imMKCLs (Fig. 2, E and F). Furthermore, comparative experiments in the presence or absence of KP457 revealed no differences in the number or function of the resulting platelets (Fig. S1, G–I). Despite prior use of KP457 in culture, our data underscore its necessity for future iPSC-platelet manufacturing protocols.

In cells, including platelets, intracellular ATP production is supported not only by mitochondrial oxidative phosphorylation but also by glycolysis. While earlier studies reported that glycolysis is the predominant source of ATP in platelets (Akkerman and Holmsen, 1981), recent advances in analytical techniques have shown that mitochondrial ATP production may actually be dominant, accounting for approximately 75% of total ATP generation via oxidative phosphorylation (Jedlička et al., 2021). These findings suggest that mitochondrial dysfunction can cause intracellular ATP depletion to an extent sufficient to impair flippase activity and ultimately trigger GPIbα shedding, as demonstrated by treatment with the depolarizing agent ionomycin (Fig. 3 E).

Mechanistically, turbulence was found to optimize F-actin dynamics by finely tuning the balance between polymerization and depolymerization, thereby ensuring uniform mitochondrial distribution within maturing megakaryocytes and promoting efficient platelet biogenesis. The reduction in F-actin levels under turbulent conditions during the late maturation stage (as noted

earlier) highlights this critical window for enhanced GPIbα$^+$ iPSC-platelet generation. To validate this, we treated cultures with compounds targeting F-actin (Latrunculin A, Cytochalasin D), cofilin (SZ-3), the Arp2/3 complex (CK-666), and Drp1 (Mdivi-1). Each of these interventions led to a dose-dependent decline in GPIbα$^+$ iPSC-platelet output, although mitochondrial membrane potential (MMP) levels remained relatively unchanged.

Interestingly, previous work has implicated actin polymerization in promoting GPIbα shedding (Zhou et al., 2022). While Cytochalasin D treatment paradoxically increased F-actin levels, Latrunculin A reduced both F-actin content and GPIbα expression. Actin filaments were visualized using a fluorescent derivative of the cell-permeable F-actin–stabilizing compound jasplakinolide (Milroy et al., 2012; Merino et al., 2020). As jasplakinolide stabilizes actin filaments, increases in F-actin signal should be interpreted with caution (Pospich et al., 2020; Merino et al., 2020). Nevertheless, the data support a critical role for actin filament dynamics in mitochondrial distribution and GPIbα expression. These findings suggest that GPIbα shedding is not simply dictated by polymerized actin quantity but rather by the dynamic equilibrium of actin turnover. Consistent with this, imaging analyses revealed uniform mitochondrial distribution in imMKCLs exposed to turbulent flow. Given that actin treadmilling is crucial for organelle distribution from mother to daughter cells (Moore et al., 2021), and that neuronal mitochondrial transport relies predominantly on microtubules, our results instead emphasize an actin-centric mechanism in megakaryocytes. Together, these data support a model in which actin treadmilling—characterized by continuous polymerization and depolymerization—governs the even allocation of mitochondria and is fundamental to the production of functional platelets.

While this study underscores the pivotal role of turbulence in regulating F-actin dynamics and mitochondrial distribution, the precise mechanotransductive link between turbulent forces and cytoskeletal modulation in megakaryocytes remains to be further defined. Future work utilizing

confocal and super-resolution microscopy, in conjunction with analysis of specific actin-binding proteins, will be critical for dissecting actin dynamics in ex vivo megakaryocyte cultures. Further clarification of the roles of cofilin and the Arp2/3 complex in this context is also warranted. Finally, identifying the extracellular cues that influence intracellular actin organization will provide valuable insights for refining iPSC-platelet manufacturing strategies.

In summary, our findings reveal that turbulent flow is a key regulator of actin-dependent mitochondrial positioning, a process central to the generation of high-quality iPSC-platelets. These insights not only advance our understanding of platelet biogenesis but also offer practical avenues for improving the scalability and quality of iPSC-platelet manufacturing.

Material and method:

Cell

The Clone 17 imMKCL, originally established by the Eto group at Kyoto University, was used in all experiments except those related to GPIX knockout (GPIX-KO). The GPIX-KO cells were generated by the Freson group at the KULeuven from clone 7 imMKCL, using the CRISPR-Cas9 system to introduce a frameshift variant in the GP9 gene creating a homozygous GPIX deletion. Immunoblot analysis confirmed absent expression of GPIX and GPIbα in the GPIX-KO cells (De Wispelaere et al., in revision, *HemaSphere*).

Culture medium

The basal medium consisted of IMDM (Sigma-Aldrich, #I3390) supplemented with 2 mM L-glutamine (Thermo Fisher Scientific, #25030-081), insulin-transferrin-selenium (Thermo Fisher Scientific, #41400-045), 50 µg/mL ascorbic acid (Sigma-Aldrich, #A4544), and 450 µM 1-thioglycerol (Sigma-Aldrich, #M6145). For the Dox-ON culture, the basal medium was further supplemented with 15% fetal bovine serum (FBS; Sigma-Aldrich, #172012), 50 ng/mL animal

component-free recombinant human stem cell factor (SCF; Wako, #193-15513), 200 ng/mL TA-316 (Nissan Chemical), and 5 μg/mL doxycycline (Clontech, #631311). For the Dox-OFF culture, the basal medium was supplemented with human plasma (Japan Blood Products Organization), 1 IU/mL enoxaparin sodium (Kaken Pharmaceutical Co., Ltd.), 50 IU/mL Cleactor Intravenous Infusion (Eisai Co., Ltd., #3959407D2034), 50 ng/mL SCF, 200 ng/mL TA-316, 0.75 μM SR-1 (Calbiochem) or 0.5 μM GNF-351 (Calbiochem), and 10 μM Y-27632 (Wako) or 0.5 μM Y-39983 (MedChemExpress).

Cell culture

Dox-ON proliferation culture

The expansion culture (Dox-ON stage) was performed as previously described (Ito et al., 2018). Briefly, cells were passaged twice a week, maintaining cell densities between 1×10^5 and 2×10^6 cells/mL throughout the culture period. For all experiments except those using the VerMES bioreactor, the Dox-ON culture was conducted in 10-cm culture dishes (Thermo Scientific, #150466). For larger-scale experiments using the VerMES bioreactor, cell expansion was achieved through sequential upsizing: starting with 10-cm static dishes, followed by 125 mL and 500 mL Corning® Erlenmeyer cell culture flasks (Sigma-Aldrich, #431143 and #431145) under shaking conditions using a Lab-Therm shaker (Kuhner), and finally scaled up to a 10 L CELLBAG™ operated with the ReadyToProcess WAVE™ 25 system (Cytiva, #CB0010L10-03) under rocking motion.

Dox-OFF differentiation culture

For platelet production following imMKCL maturation (Dox-OFF stage), approximately $1 - 3 \times 10^5$ cells/mL were cultured for 6 days under one of the following conditions: in 10-cm culture dishes (Thermo Scientific, #150466), in 125 mL Corning® Erlenmeyer cell culture flasks (Sigma-Aldrich, #431143) under shaking conditions using a Lab-Therm shaker (Kuhner), or in

a VerMES bioreactor (SATAKE Co., Ltd., Saitama, Japan). The VerMES bioreactor was equipped with vertically oscillating two-stage mixing blades, and the optimal operating conditions for the 8 L VerMES were a stroke of 40 mm and a speed of 150 mm/s.

Human platelets

Donor-derived human platelets were provided from the Japanese Red Cross Society. Human platelets and plasma were used in compliance with the Guidelines on the use of Donated blood in R&D, etc. from Ministry of Health, Labour and Welfare of Japan.

Flow cytometry analysis

Flow cytometric analysis was performed using a FACSLyric™ cytometer (BD Biosciences) for the experiments described below (Platelet count, Annexin V binding assay, Activation of platelets, Flippase and scramblase activity, Ca assay, Factor V assay, Calcein AM assay, Evaluation of mitochondria related parameters, and Detection of F-actin). The following antibodies and reagents were used: anti-human CD41-APC (BioLegend, #303710), anti-human CD41-PE (BioLegend, #303706), anti-human CD42b-PE (BioLegend, #303906), anti-human CD42b-PerCP (BioLegend, #303910), anti-human CD42a-FITC (eBioscience, #11-0428-42), anti-human GPVI-Brilliant Violet 421 (BD Biosciences, #743941), anti-human CD62P-Brilliant Violet 421 (BioLegend, #304926), PAC-1-FITC (BD Biosciences, #340507), and Annexin V-FITC (BD Biosciences, #556419). All flow cytometry data were analyzed using FlowJo v10 (BD Biosciences).

Platelet count

The number of platelet particles per imMKCL cell was defined as the total count of $CD41^+$ iPSC-derived platelets (iPSC-platelets) or $CD41^+CD42b^+$ iPSC-platelets on the indicated day,

divided by the number of imMKCL cells on day 0 of the Dox-OFF culture. Platelet counts were determined using Trucount™ Tubes (BD Biosciences, #340334).

Annexin V binding assay

Staining with FITC-conjugated Annexin V, together with anti-CD41 and anti-CD42b antibodies, was performed in Annexin V binding buffer (BD Biosciences, #556454) supplemented with 1 μM $CaCl_2$. For positive and negative controls, 20 μM ionomycin (Wako, #091-05833) or EDTA (Nacalai Tesque, #06894-14) were added to each sample, respectively, prior to staining.

Activation of platelets

Platelet activation was evaluated by measuring PAC-1 binding and P-selectin (CD62P) expression, following the protocol described in our previous study (Sone et al., 2021). Briefly, culture suspensions of iPSC-platelets were stimulated with or without 0.2 μM phorbol 12-myristate 13-acetate (PMA) or a combination of 100 μM adenosine diphosphate (ADP) and 40 μM thrombin receptor-activating peptide 6 (TRAP6). The cells were then incubated with anti-CD62P, anti-human CD41a, and PAC-1 antibodies for 30 minutes at room temperature. After incubation, the samples were diluted in HEPES-Tyrode buffer (10 mM HEPES, 15 mM $NaHCO_3$, 138 mM NaCl, 5.5 mM glucose, 2.6 mM KCl, 1 mM $MgCl_2$, and 2 mM $CaCl_2$) and analyzed by flow cytometry.

Flippase and scramblase activity

Evaluations of flippase and scramblase activity were performed as previously described (Miyata and Segawa, 2022). Briefly, iPSC-derived platelets were stained with 0.5 μM 18:1-06:0 NBD-PS (Merck, #810194P) for 20 minutes or 0.5 μM 16:0-06:0 NBD-PC (Merck, #810130P) for 60

minutes, together with anti-CD41 and anti-CD42b antibodies. After staining, 2% BSA (prepared by diluting a 10% stock solution; Merck, #A1595) was added to remove non-specific binding. To confirm staining specificity, 60 μM ionomycin was added during NBD-PC or NBD-PS staining.

Ca assay

iPSC-derived platelets were stained with 3 μL Fluo-4 AM (Dojindo Molecular Technologies, Inc., #F312) together with anti-CD41 and anti-CD42b antibodies for 20 minutes. To assess calcium influx in response to stimulation, 2 μM ionomycin was added immediately prior to flow cytometric analysis.

Factor V assay

Human Factor V (Haematologic Technologies Inc., #HCV-0100) was fluorescently labeled using the Fluorescent Protein Labeling Kit (Thermo Fisher Scientific, #A10235) prior to its addition to imMKCL cultures on Day 3 of the Dox-OFF stage. The incorporation of Factor V into the produced platelets was evaluated on Day 6.

Calcein AM assay

The uptake of Calcein-AM (FUJIFILM Wako Pure Chemical Corporation, #341-07901) by iPSC-derived platelets was assessed on Day 6 of the Dox-OFF culture. Platelets were stained with 2 μM Calcein-AM together with anti-CD41 and anti-CD42b antibodies for 30 minutes.

Evaluation of mitochondria related parameters

The reagents and their concentrations used in these experiments were as follows: 100 μM BioTracker ATP-Red Live Cell Dye (Merck, #SCT045) for ATP content; 1 μM CellROX Deep Red Flow Cytometry Assay Kit (Thermo Fisher Scientific, #C10491) for reactive oxygen

species (ROS) production; 100 nM MitoTracker Deep Red (Thermo Fisher Scientific, #M22426) or the MT-1 MitoMP Detection Kit (Dojindo Molecular Technologies, Inc., #MT13) for mitochondrial membrane potential; 1:10,000 dilution of PicoGreen (Thermo Fisher Scientific, #P11495) for mitochondrial DNA detection; and 50 nM MitoTracker Green (Dojindo Molecular Technologies, Inc., #MT10) for mitochondrial presence. Platelets or imMKCLs were stained with each reagent together with anti-CD41 and anti-CD42b antibodies for 30 minutes.

Detection of F-actin

For F-actin specific detection, platelets or imMKCLs were stained with SPY555-FastAct (Cytoskeleton, Inc., #CY-SC205) together with anti-CD41 antibody for 2 hours.

Metabolic flux analysis

imMKCL cells were seeded into each well of an XF96 microplate pre-coated with 0.1% poly-L-lysine and used to measure the oxygen consumption rate (OCR) using an Agilent Seahorse XF Pro analyzer. The assay was performed with the Seahorse XF Cell Mito Stress Test Kit (Agilent Technologies, #103015-100) and XF RPMI Medium, pH 7.4 (Agilent Technologies, #103576-100). After seeding, the plate was centrifuged at 1,500 × *g* for 1 minutes to form a monolayer, then equilibrated for 10 minutes at 37 °C in a non-CO_2 incubator before starting the assay. The Cell Mito Stress Test protocol included sequential injections of oligomycin (1 μM), FCCP (2 μM), and a mixture of rotenone and antimycin A (1 μM each). For each injection, four measurement cycles were performed, consisting of 3 minutes of mixing followed by 3 minutes of measurement. OCR data were analyzed using Wave 2.6 software (Agilent Technologies), and key mitochondrial parameters were calculated using the Agilent Seahorse Analytics online tool.

Protein Quantification Using Wes™

Protein expression levels were analyzed using the Wes™ automated capillary electrophoresis–based immunoassay system (ProteinSimple). Cells were lysed in RIPA buffer supplemented with protease and phosphatase inhibitors, and protein concentrations were measured using the BCA Protein Assay Kit (Thermo Fisher Scientific). The following antibodies were used: anti–β-actin (Cell Signaling Technology, #4970), anti-TOM20 (Abcam, #ab186735), and Anti-Rabbit Detection Module Chemiluminescence (ProteinSimple, #DM-001). Equal amounts of total protein, blocking reagent, primary and secondary antibodies, and chemiluminescent substrate were loaded into the Wes™ assay plate according to the manufacturer's instructions. Chemiluminescent signals were acquired and quantified using Compass for Simple Western software (ProteinSimple). Protein levels of β-actin were normalized to TOM20.

Electron Microscopy

Platelet pellets were fixed with a mixture of 0.5% glutaraldehyde and 2% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4) for 60 minutes at 4 °C. After washing with phosphate buffer, the samples were post-fixed with 1% osmium tetroxide in phosphate buffer for 60 minutes on ice. Following dehydration, pellets were infiltrated with and embedded in epoxy resin. Ultrathin sections (60–80 nm thick) were cut, stained with 2% uranyl acetate in 70% methanol and Reynolds' lead citrate, and examined using a transmission electron microscope operating at 80 kV (HT-7700; Hitachi, Tokyo, Japan).

Live cell imaging

For live-cell imaging using confocal microscopy, u-Dish 35 mm Quad ibiTreat sterilized dishes (Nippon Genetics, #ib80416), pre-coated with 0.1% poly-L-lysine, were used. Imaging was performed using a ZEISS LSM 900 confocal microscope equipped with Airyscan 2 and a 63×/1.40 numerical aperture oil-immersion objective. The following reagents were used for

staining imMKCLs or platelets: APC-conjugated anti-human CD41 antibody, PerCP-conjugated anti-human CD41 antibody, MitoTracker Green, SPY555-FastAct, Plasmem Bright Green (Dojindo Laboratories, #P504), and Hoechst 33342 (Thermo Fisher Scientific, #62249). Confocal images were acquired using the same system.

Evaluations of small compounds

Mdivi-1 (Sigma-Aldrich, #M0199-5MG) was added on Day 0 of the Dox-OFF culture to inhibit mitochondrial fission. Latrunculin A (FUJIFILM Wako Pure Chemical Corporation, #125-04363), Cytochalasin D (Cayman Chemical, #11330), SZ-3 (MedKoo Biosciences, #208333), and CK-666 (Selleck, S7690) were added on Day 3 of the Dox-OFF culture. Various ADAM inhibitors were used as follows: 15 μM KP-457 (Kaken Pharmaceutical), 10 μM GI254023X (Selleck, #S8660), 100 μM TAPI-1 (Selleck, #S7434), and 10 μM GM6001 (Ilomastat; Selleck, #S7157). For all experiments, dimethyl sulfoxide (DMSO) was added to control wells and was also used as the solvent for compound dilution.

Mitochondrial mAG overexpression

The CoralHue™ mitochondria-targeted monomeric Azami-Green (pMT-mAG1) plasmid was provided by the RIKEN BRC through the National BioResource Project of MEXT, Japan (Cat. #RDB18311). A PiggyBac transposon vector system was used to establish stable mitochondrial labeling in imMKCLs. The gene of interest (GOI), encoding CoralHue mitochondria-targeted monomeric Azami-Green, was amplified from pMT-mAG1 (Karasawa et al., 2003) via PCR. The amplified GOI was inserted into the backbone vector using the In-Fusion® HD Cloning Kit (Clontech, #639649).

Bulk RNA-sequencing analysis

Total RNA was extracted from cultured imMKCLs at Dox-OFF Day 4 using the RNeasy® Plus Micro Kit (Qiagen, #74034). For each sample, up to 10 ng of total RNA was processed using the SMART-Seq v4 Ultra Low Input RNA Kit for Sequencing (Clontech, #634890). Complementary DNA (cDNA) was fragmented using an S220 Focused-ultrasonicator (Covaris), and the cDNA library was prepared and amplified with the NEBNext® Ultra™ DNA Library Prep Kit for Illumina (New England Biolabs, #E7370L). Library size distribution was evaluated using a Bioanalyzer with the Agilent High Sensitivity DNA Kit. Sequencing was performed on an Illumina NextSeq 500. FASTQ files were generated using *bcl2fastq* v2.20. Adapter sequences and low-quality bases were trimmed from raw sequencing reads using *cutadapt* v4.1 (Kechin et al., 2017). Trimmed reads were aligned to the human reference genome (hg38) using *STAR* v2.7.10a (Dobin et al., 2013) with the GENCODE annotation file (release 32, GRCh38.p13) (Frankish et al., 2019). Uniquely mapped reads were quantified at the gene level using *htseq-count* v2.0.2 (Anders et al., 2015) with the same GENCODE GTF file. Gene expression levels were calculated and expressed as transcripts per million (TPM).

Statistical analysis

Statistical analysis was performed using GraphPad Prism 10 (GraphPad Software, La Jolla, CA). Data are expressed as the mean ± standard error of the mean (SEM). To determine statistical significance, an unpaired two-tailed Student's t-test was used. Details of the sample size used, statistics, and statistical significance are indicated in each figure legend.

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Author contributions

E.N. and Y.H. conducted most experiments and analyzed data. K.Freson., K.D.W., and C.T. generated GPIX-KO clone 7 imMKCLs. A.S. conducted the platelet transmission electron microscopy and analyzed data. K. Fujio. constructed the vector system and analyzed related results. S.N. and S.S supervised experimental design. E.N., Y.H., K.E wrote the manuscript. K.E. edited manuscript.

Declarations of competing interests

K.E. is a founder of Megakaryon Co. Ltd. and currently has no stock. K.E. previously received the collaborating research budget from Megakaryon Co. Ltd. and Otsuka Pharmaceutical Co. Ltd. The interests of K.E. have been reviewed and are managed by Kyoto University in accordance with its conflict-of-interest policies.

Other authors declare no conflicts of interest.

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746 **Figure Legends**

747

748 **Figure 1. Turbulence enhances high-quality iPSC-PLT production, as indicated by**

749 **increased GPIbα expression and mitochondrial membrane potential.**

750 (A) Schematic illustration of three culture systems: dish (static), flask (suboptimal turbulence),

751 and VerMES (optimal turbulence).

752 (B–D) Analysis of integrin αIIb (CD41) and GPIbα expression on day 6 platelets derived from

753 each culture condition. Platelets were defined as $CD41^+$ particles.

754 (B) Representative flow cytometry plots of platelets generated under dish (left), flask (middle),

755 and VerMES (right) conditions.

756 (C) Quantification of the number of $GPIb\alpha^+$ (orange) and $GPIb\alpha^-$ (blue) platelets produced per

757 megakaryocyte.

758 (D) Proportion of $GPIb\alpha^+$ (orange) and $GPIb\alpha^-$ (blue) platelets. Data are presented as mean ±

759 SEM (n = 3). Statistical significance was determined using an unpaired two-tailed t-test (***$p <$

760 0.001).

761 (E) Representative flow cytometry plots showing Calcein-AM fluorescence (left) and surface

762 expression of GPIbα and CD41 (right) in day 6 platelets cultured in a dish (top) or flask

763 (bottom).

764 (F) Representative flow cytometry plots showing mitochondrial membrane potential

765 (MitoTracker Deep Red) and GPIbα expression in day 6 platelets cultured in a dish (left), flask

766 (middle), or VerMES (right).

767 (G, H) Platelet production per megakaryocyte in a day 4 culture swap experiment.

768 (G) Schematic diagram of the experimental design for culture condition swapping.

769 (H) Quantification of platelets produced per megakaryocyte under the following conditions:

770 dish–dish, flask–dish, dish–flask, and flask–flask. Data are presented as mean ± SEM (n = 3).

771 Statistical analysis was performed using an unpaired two-tailed t-test (ns, not significant; *p <
772 0.05).
773
774 **Figure 2. Mitochondrial activity regulates GPIbα expression.**
775 (A) Representative flow cytometry plots and histogram overlays showing staining for
776 mitochondrial DNA (PicoGreen), mitochondrial content (MitoTracker Green), mitochondrial
777 membrane potential (MT-1), reactive oxygen species (ROS; CellROX), and adenosine
778 triphosphate (ATP; BioTracker ATP Red) in GPIbα^{+} (red) and GPIbα^{-} (blue) day 6 platelets
779 cultured under static conditions. Unstained controls are shown in gray.
780 (B) Representative flow cytometry plots showing mitochondrial membrane potential
781 (MitoTracker Deep Red) and phosphatidylserine exposure (Annexin V) in day 6 platelets
782 cultured in a dish (left) or flask (right).
783 (C) Representative flow cytometry plots showing GPIbα staining and mitochondria-specific
784 mAzami Green fluorescence in day 6 platelets derived from dish (left) or flask (right) cultures.
785 (D) Representative histograms showing GPIbα expression (far left, middle right) and
786 mitochondrial membrane potential (MitoTracker Deep Red; middle left, far right) in control
787 (blue) and after treatment with DMSO (red), KP457 (orange), GI254023X (green), TAPI-1
788 (dark green), or GM6001 (purple) in day 6 platelets prior to FCCP treatment, from dish (left) or
789 flask (right) cultures.
790 (E, F) Comparison of platelet production and mitochondrial membrane potential between wild-
791 type and GPIX-knockout (KO) imMKCLs.
792 (E) Quantification of the percentage of CD41^{+}/GPIbα^{+} platelets produced by wild-type (green)
793 or GPIX-KO (orange) imMKCLs. Data are presented as mean ± SEM (n = 3). Statistical
794 significance was determined using an unpaired two-tailed t-test (***p < 0.001).
795 (F) Representative histograms showing mitochondrial membrane potential in platelets derived

from wild-type (green, middle) or GPIX-KO (orange, bottom) imMKCLs. Unstained control is shown in gray (top).

Figure 3. Mitochondrial ATP production supports flippase-mediated membrane asymmetry.

(A) Schematic illustration of the assay used to evaluate flippase and scramblase activity.

(B, C) Representative flow cytometry plots showing surface GPIbα expression and NBD-labeled phospholipid incorporation in day 6 platelets cultured in a dish (left) or flask (right). (B) NBD–phosphatidylserine (NBD-PS); (C) NBD–phosphatidylcholine (NBD-PC).

(D, E) Flow cytometry analysis of GPIbα expression, intracellular calcium levels, and ATP content in day 6 platelets derived from dish and flask cultures.

(D) Representative plots and histograms showing surface GPIbα expression and intracellular calcium levels (Fluo-4) in platelets from dish (left) and flask (right) conditions.

(E) Representative flow cytometry plots showing surface GPIbα expression and intracellular ATP levels (BioTracker ATP Red) in platelets cultured in a dish (left) or flask (right).

(F) Schematic model illustrating differences in GPIbα expression between high-quality (left) and low-quality (right) iPSC-derived platelets.

Figure 4. Turbulent culture conditions promote uniform mitochondrial distribution in imMKCLs.

(A, B) Confocal imaging and fluorescence intensity analysis of day 4 maturing imMKCLs cultured under static (dish) or turbulent (flask) conditions.

(A) Representative confocal images of day 4 maturing imMKCLs. Top panels show original images (scale bars, 10 μm); bottom panels show magnified views (scale bars, 5 μm) of cells cultured in a dish (left) or flask (right). Mitochondria were stained with MitoTracker Green

(green), F-actin with SPY555-FastAct (red), and nuclei with Hoechst 33342 (blue).

(B) Fluorescence intensity profiles of F-actin (red) and mitochondria (blue) along the central axis (yellow line in A, magnified images).

(C) Quantification of the percentage of GPIbα^{+} (red) and GPIbα^{-} (blue) platelets on day 6 following Mdivi-1 treatment. Data are shown as mean ± SEM (n = 3). Statistical significance was determined using an unpaired two-tailed t-test (*$p < 0.05$; **$p < 0.01$).

(D) Oxygen consumption rate (OCR) of day 4 maturing imMKCLs cultured in a dish (red) or flask (blue), measured using the Seahorse Flux Analyzer.

(E) Representative histograms showing mitochondrial membrane potential (MitoTracker Deep Red) in day 6 imMKCLs (left) and iPSC-derived platelets (right) cultured in a dish (top, pink) or flask (bottom, blue).

Figure 5. Turbulence regulates actin dynamics to promote high-quality platelet production.

(A–C) Transcript levels of cytoskeletal genes related to actin (A), tubulin (B), and myosin (C) in day 4 maturing imMKCLs cultured in a dish or flask. Gene expression is shown as transcripts per million (TPM). Data are presented as mean ± SEM (n = 3). Statistical analysis was performed using an unpaired two-tailed t-test (ns, not significant).

(D, E) Protein levels of β-actin normalized to TOM20 in day 5 maturing imMKCLs cultured in a dish (orange) or flask (purple).

(D) Representative Simple Western (Wes) images.

(E) Quantification of β-actin expression. Data are presented as mean ± SEM (n = 3). Statistical analysis was performed using an unpaired two-tailed t-test (ns, not significant).

(F) Fold change in F-actin levels (SPY555-FastAct signal) from day 1 to day 6 in maturing imMKCLs cultured in a dish (orange), flask (purple), or VerMES (green). Data are presented as mean ± SEM (n = 3). Statistical comparisons were performed independently on day 5 and day 6

between dish and flask, and between dish and VerMES, using an unpaired two-tailed t-test. (G) Representative histograms showing surface GPIbα expression (left), phosphatidylserine exposure (Annexin V binding, middle), and mitochondrial membrane potential (MitoTracker Deep Red, right) in day 6 iPSC-derived platelets (iPSC-PLTs) cultured with Latrunculin A at 0.1 μM (dark green), 0.3 μM (lime green), 1 μM (orange), 3 μM (blue), or 10 μM (red). EDTA-treated (purple) and untreated control (mauve) samples are shown at the top. (H–J) Percentage of GPIbα^{+} (red) and GPIbα^{-} (blue) iPSC-derived platelets on day 6 following treatment with: (H) 100 nM or 1 μM Cytochalasin D, (I) 10 μM or 20 μM SZ-3, or (J) 50 μM, 100 μM, or 200 μM CK-666. Data are presented as mean ± SEM (n = 3). Statistical analysis was performed using an unpaired two-tailed t-test (ns, not significant; **$p < 0.01$; ***$p < 0.001$; ****$p < 0.0001$). (K, L) Quantification of F-actin levels in day 5 imMKCLs using SPY555-FastAct following actin-targeting compound treatment. Geometric mean fluorescence intensity is shown for cells treated on day 3 with (K) 1, 5, and 10 μM Latrunculin A, or (L) 100 nM and 1 μM Cytochalasin D. (M) Schematic model illustrating the relationship between F-actin levels, the polymerization/depolymerization state of intracellular actin, and their effects on platelet production in maturing imMKCLs.

Figure 6. Graphical summary.

(A) Turbulence reduces actin (red) polymerization during imMKCL maturation, facilitating efficient incorporation of mitochondria (green) into the resulting iPSC-derived platelets. This process is disrupted by actin polymerization inhibitors (CK-666, SZ-3), leading to the production of low-quality platelets similar to those generated under static culture conditions.

Figure 1

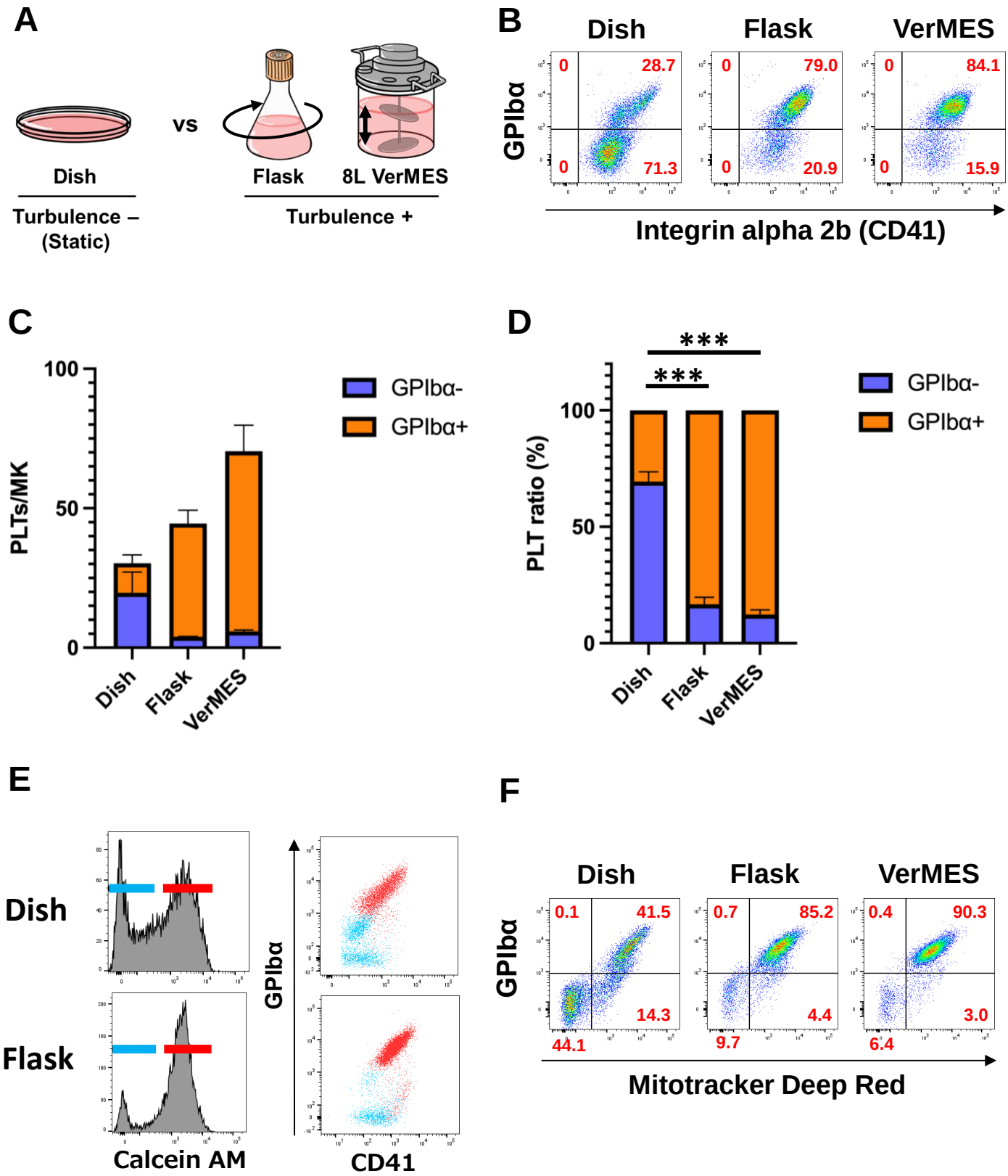
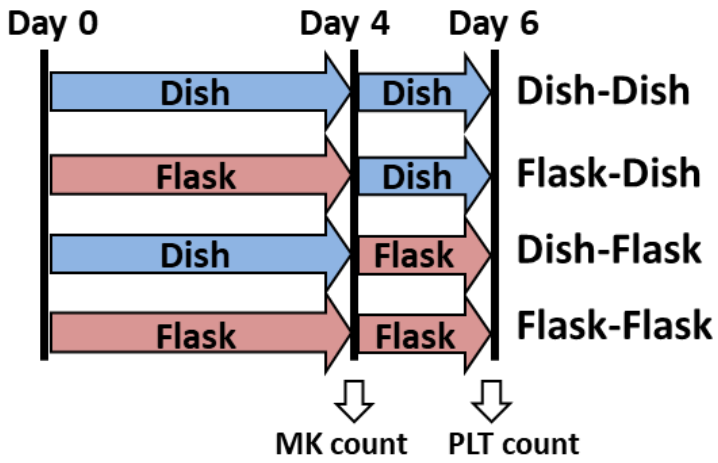

A
vs
Dish
Flask
8L VerMES
Turbulence –
(Static)
Turbulence +
B
Dish
Flask
VerMES
GPIbα
0
28.7
0
71.3
0
79.0
0
20.9
0
84.1
0
15.9
Integrin alpha 2b (CD41)
C
PLTs/MK
100
50
0
GPIbα-
GPIbα+
Dish
Flask
VerMES
D
***
***
PLT ratio (%)
100
50
0
GPIbα-
GPIbα+
Dish
Flask
VerMES
E
Dish
Flask
GPIbα
Calcein AM
CD41
F
Dish
Flask
VerMES
GPIbα
0.1
41.5
14.3
44.1
0.7
85.2
4.4
9.7
0.4
90.3
3.0
6.4
Mitotracker Deep Red

Figure 1

G


Day 0
Day 4
Day 6
Dish
Dish
Dish-Dish
Flask
Dish
Flask-Dish
Dish
Flask
Dish-Flask
Flask
Flask
Flask-Flask
MK count
PLT count

H

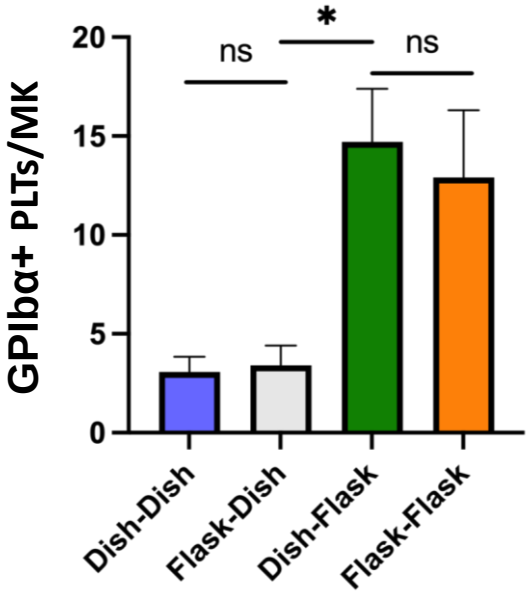

GPIbα+ PLTs/MK
20
15
10
5
0
ns
*
ns
Dish-Dish
Flask-Dish
Dish-Flask
Flask-Flask

Figure 2

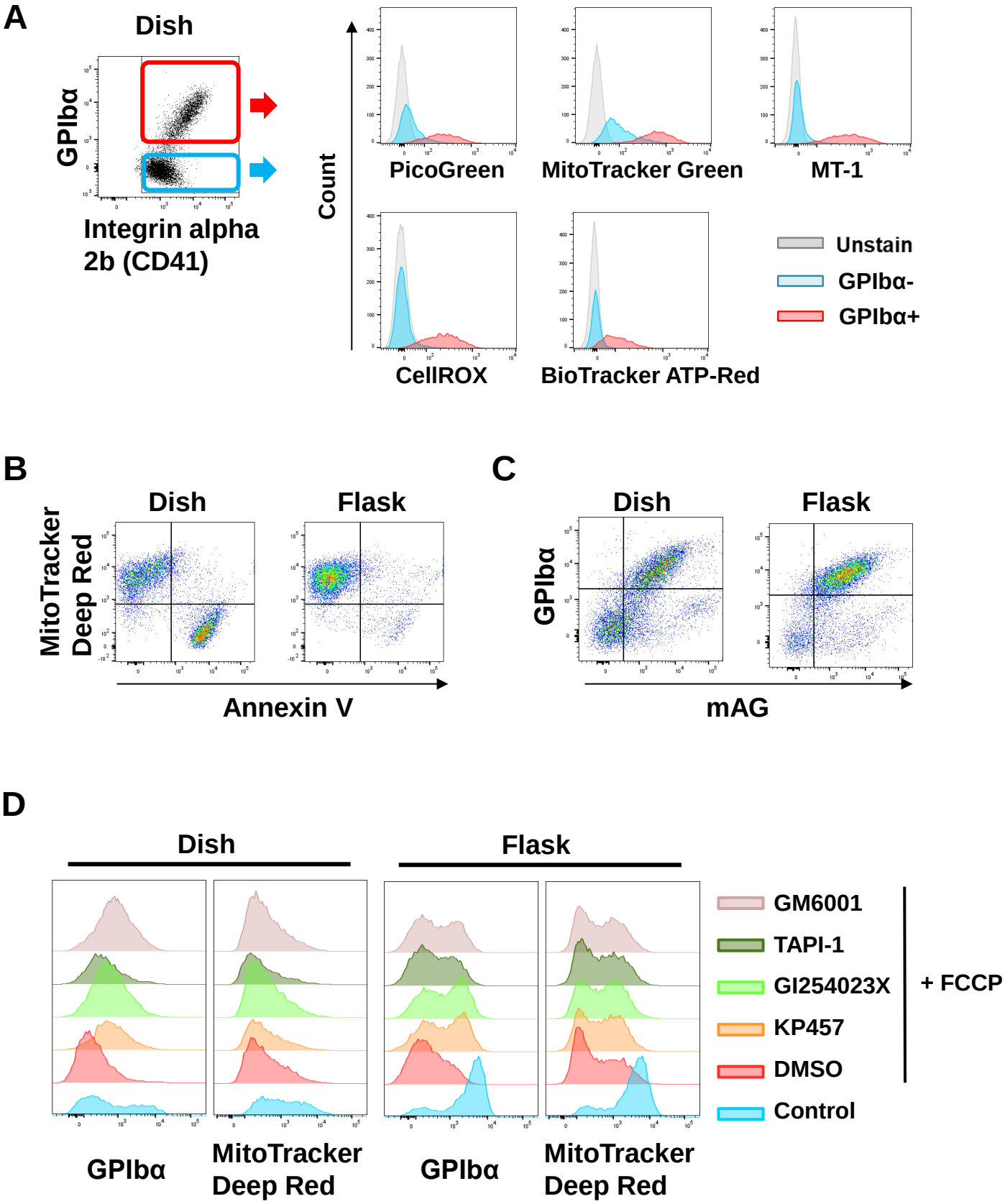

A
Dish
GPIbα
Integrin alpha 2b (CD41)
Count
PicoGreen
MitoTracker Green
MT-1
CellROX
BioTracker ATP-Red
Unstain
GPIbα-
GPIbα+
B
Dish
Flask
MitoTracker Deep Red
Annexin V
C
Dish
Flask
GPIbα
mAG
D
Dish
Flask
GPIbα
MitoTracker Deep Red
GPIbα
MitoTracker Deep Red
GM6001
TAPI-1
GI254023X
KP457
DMSO
Control
+ FCCP

Figure 2

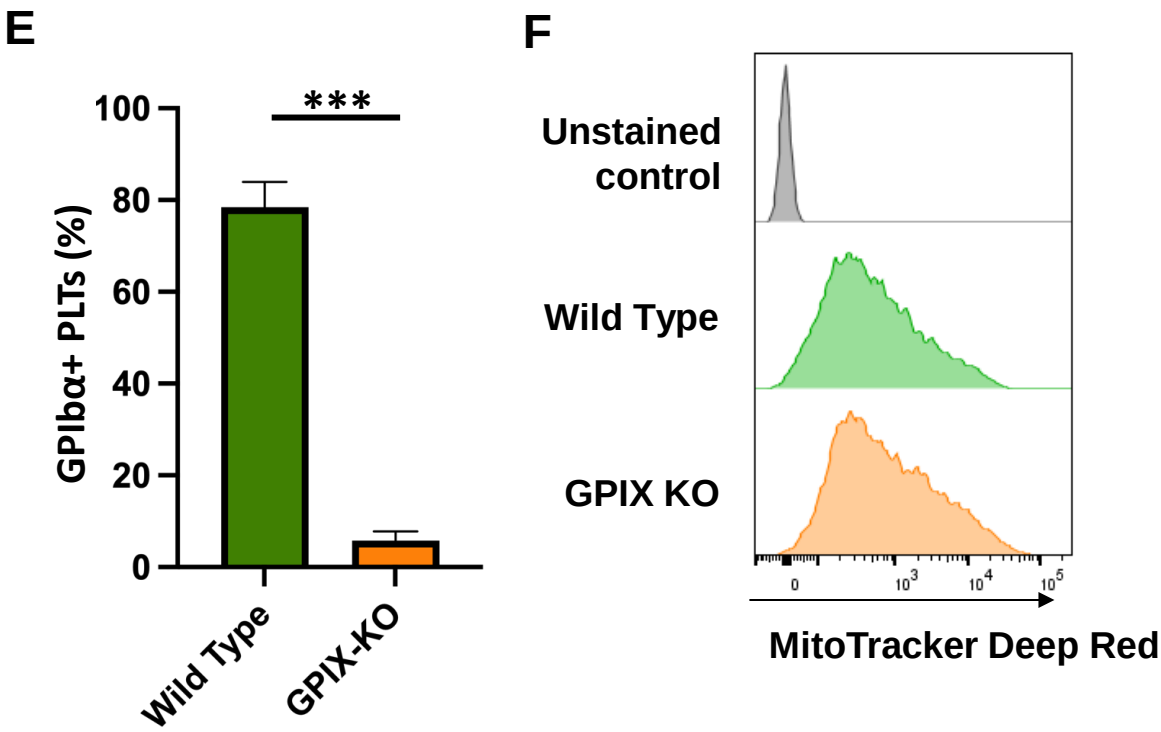

E
***
100
80
60
40
20
0
GPIbα+ PLTs (%)
Wild Type
GPIX-KO
F
Unstained control
Wild Type
GPIX KO
0
10^3
10^4
10^5
MitoTracker Deep Red

Figure 3

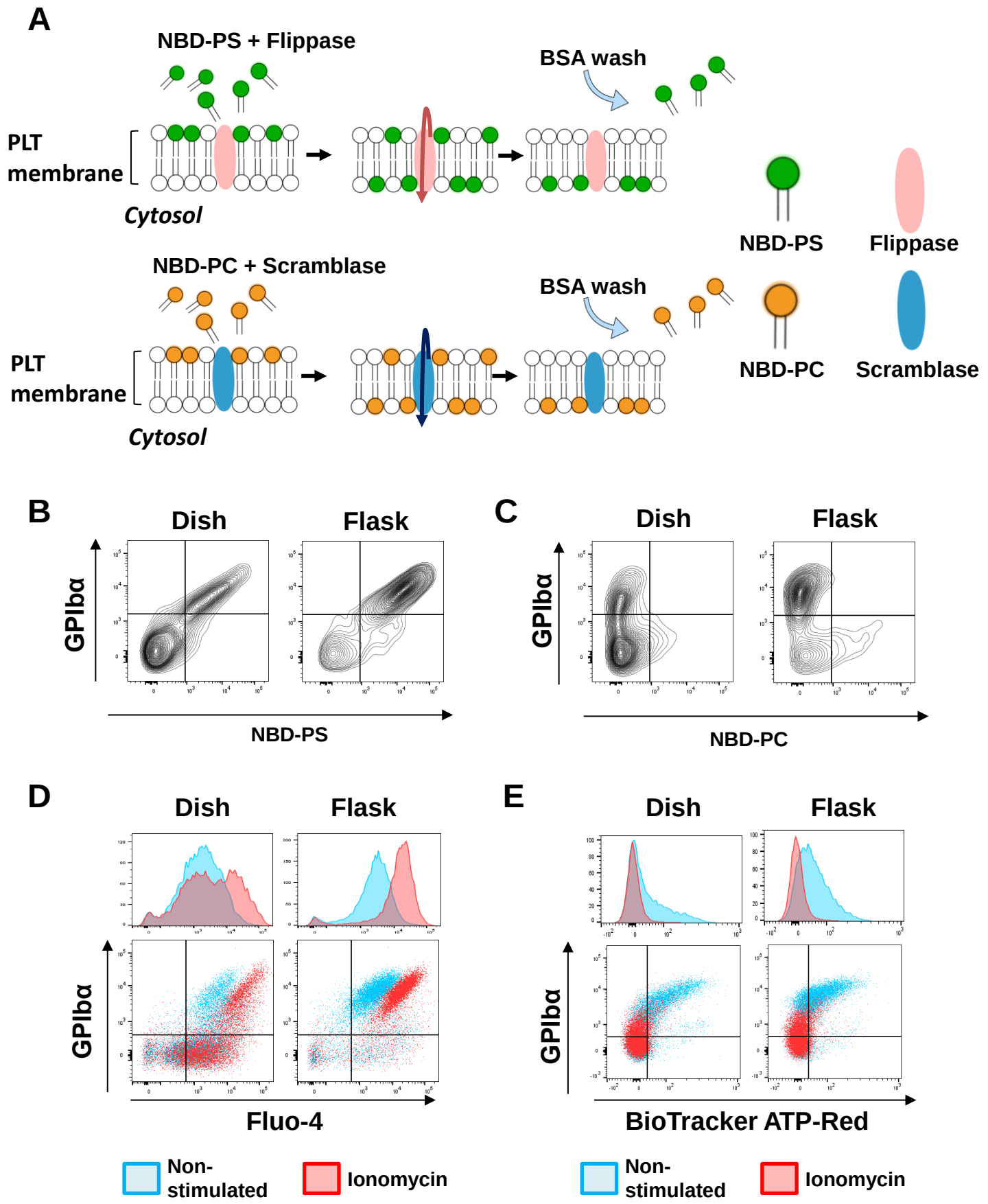

A
NBD-PS + Flippase
BSA wash
PLT membrane
Cytosol
NBD-PS
Flippase
NBD-PC + Scramblase
BSA wash
PLT membrane
Cytosol
NBD-PC
Scramblase
B
Dish
Flask
GPIbα
NBD-PS
C
Dish
Flask
GPIbα
NBD-PC
D
Dish
Flask
GPIbα
Fluo-4
Non-stimulated
Ionomycin
E
Dish
Flask
GPIbα
BioTracker ATP-Red
Non-stimulated
Ionomycin

Figure 3

E

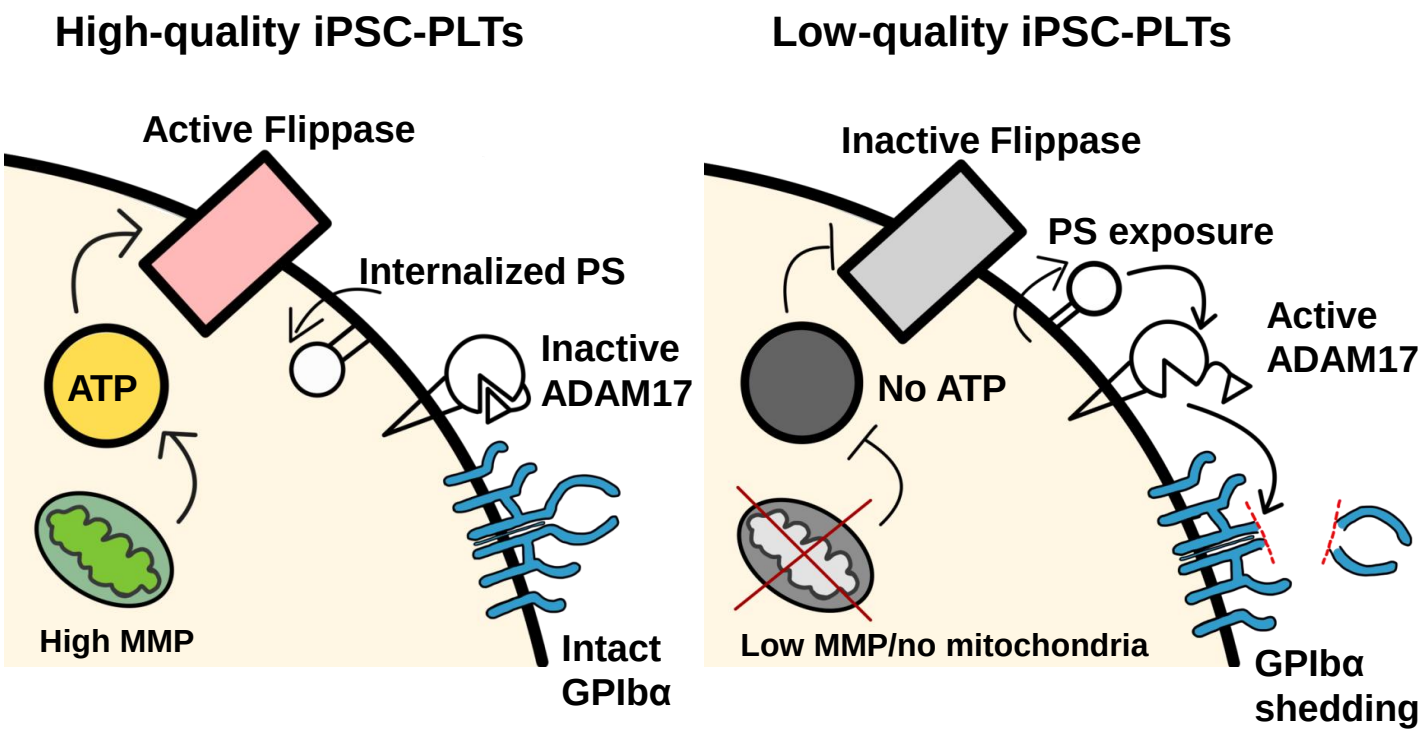
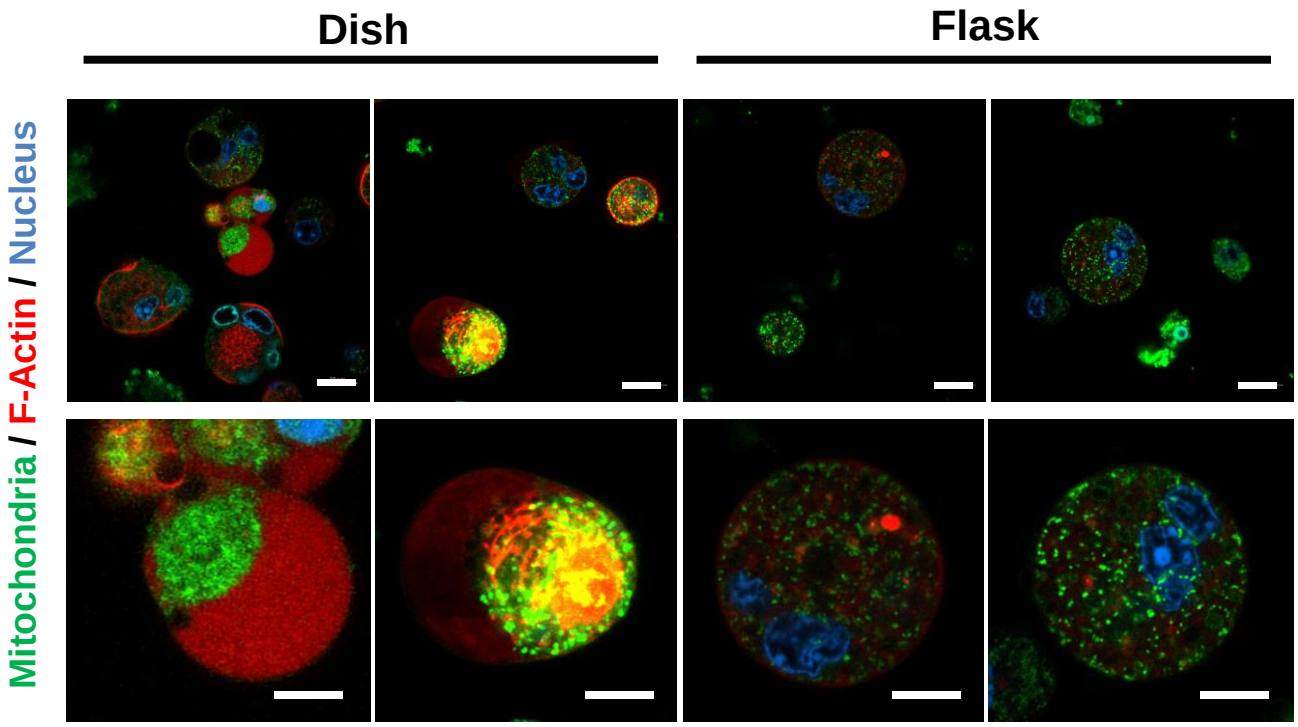

High-quality iPSC-PLTs
Active Flippase
Internalized PS
Inactive ADAM17
ATP
High MMP
Intact GPIbα
Low-quality iPSC-PLTs
Inactive Flippase
PS exposure
Active ADAM17
No ATP
Low MMP/no mitochondria
GPIbα shedding

Figure 4

A


Dish
Flask
Mitochondria / F-Actin / Nucleus

B

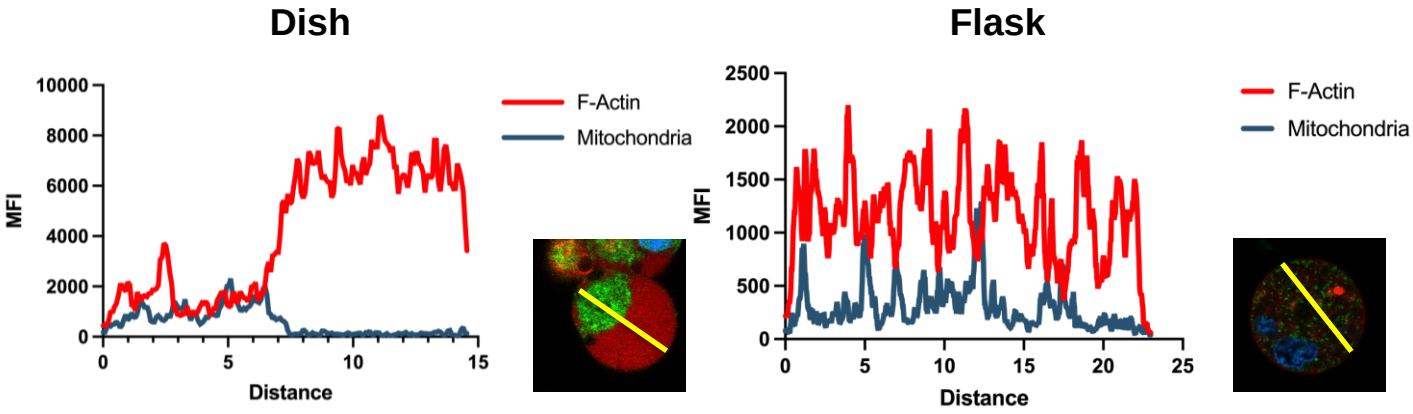
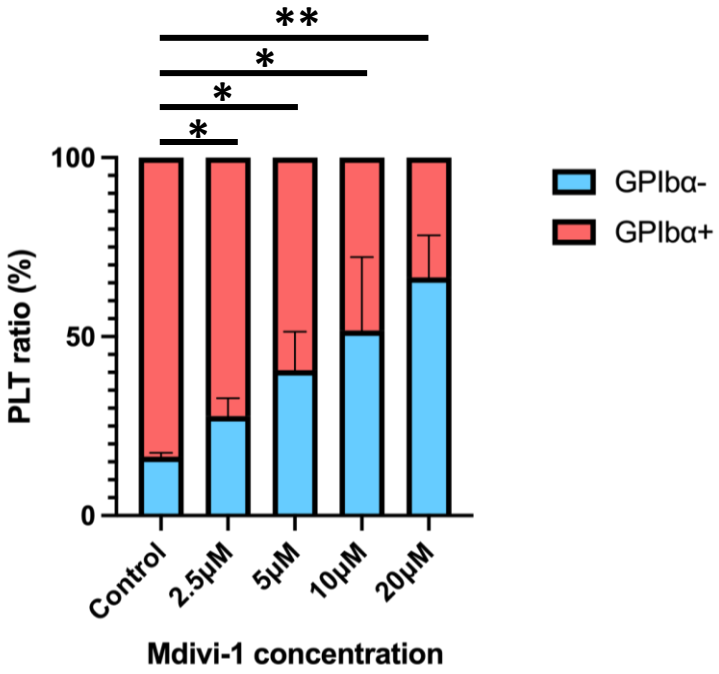
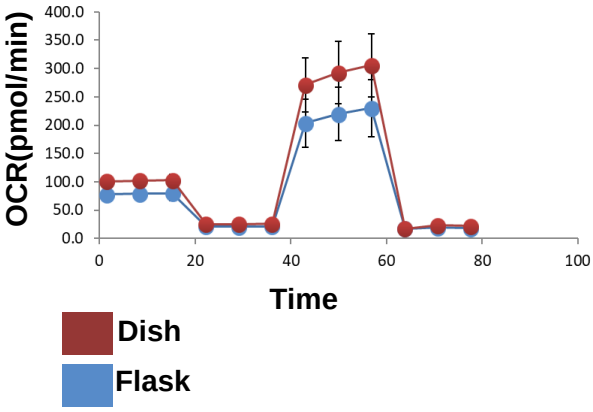

Dish
Flask
MFI
Distance
F-Actin
Mitochondria
10000
8000
6000
4000
2000
0
5
10
15
2500
2000
1500
1000
500
20
25

Figure 4

C


**
*
*
*
100
50
0
PLT ratio (%)
GPIbα-
GPIbα+
Control
2.5μM
5μM
10μM
20μM
Mdivi-1 concentration

D


OCR(pmol/min)
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0
20
40
60
80
100
Time
Dish
Flask

E

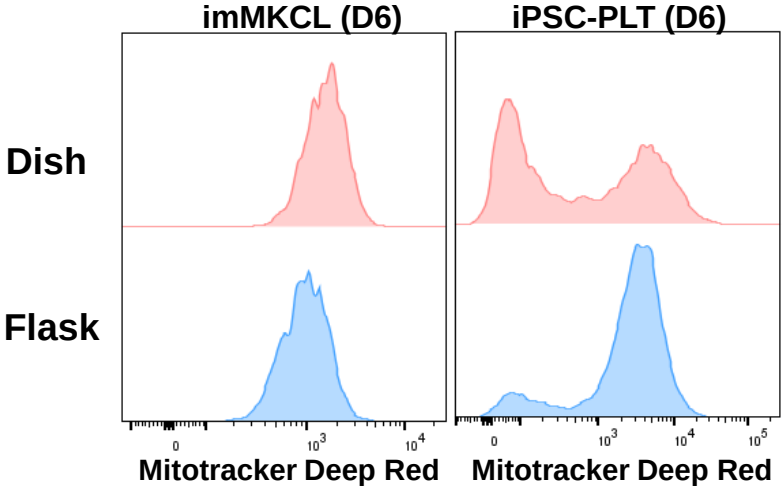
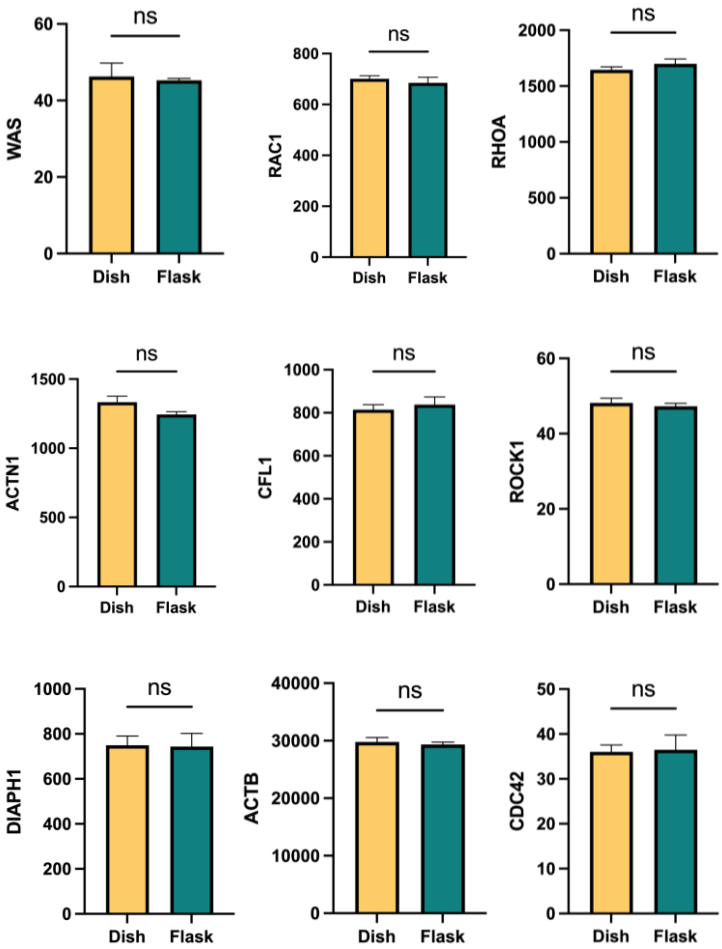
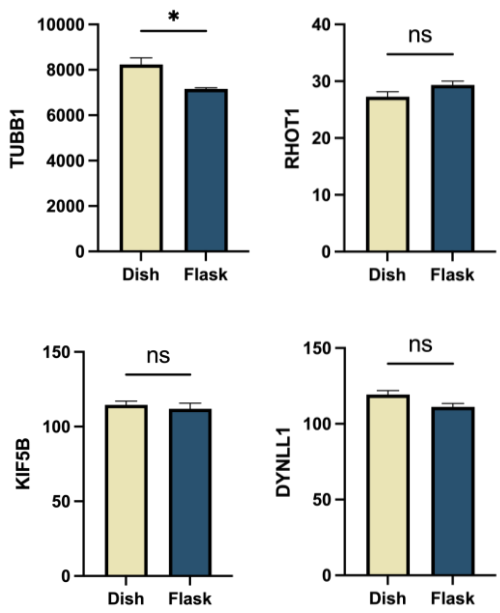

imMKCL (D6)
iPSC-PLT (D6)
Dish
Flask
0
10^3
10^4
10^5
Mitotracker Deep Red
Mitotracker Deep Red

Figure 5

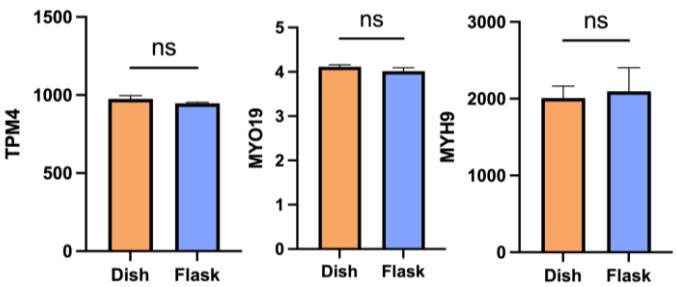
A Actin-related gene expression



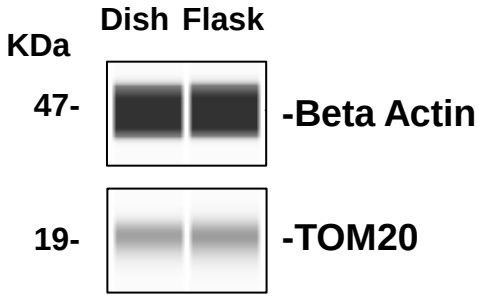
B Tubulin-related gene expression



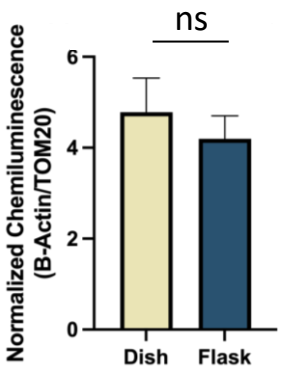
C Myosin-related gene expression



D



E



F

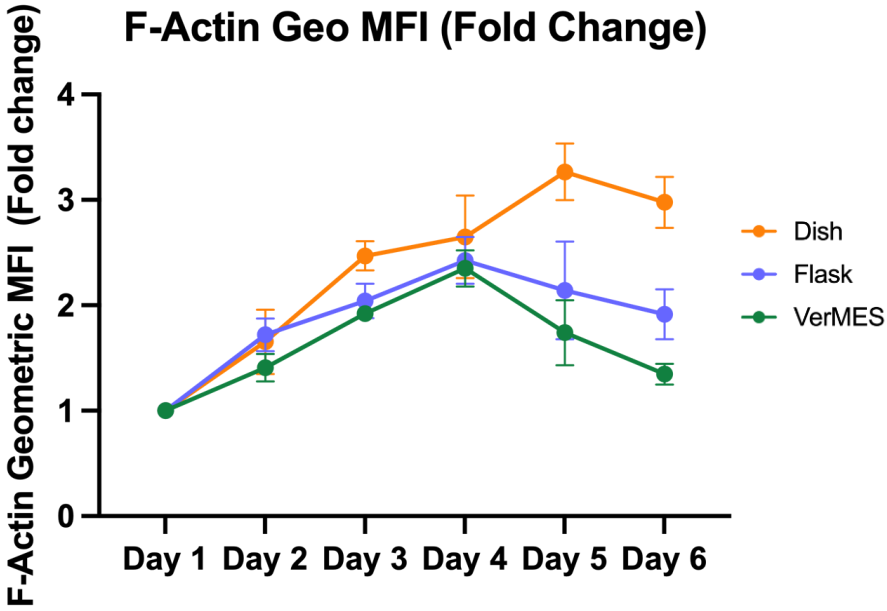
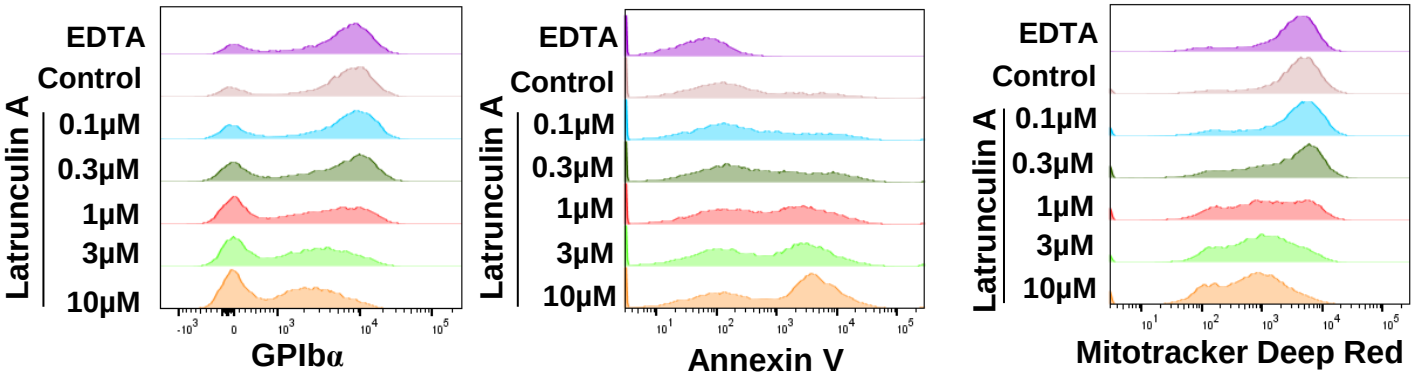
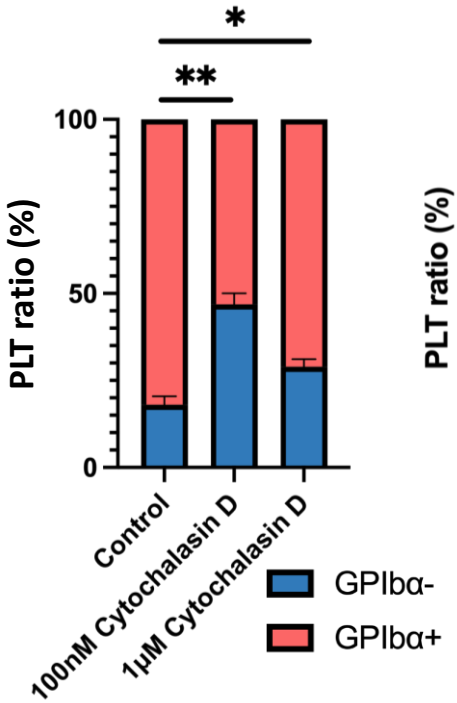


Figure 5

G



H



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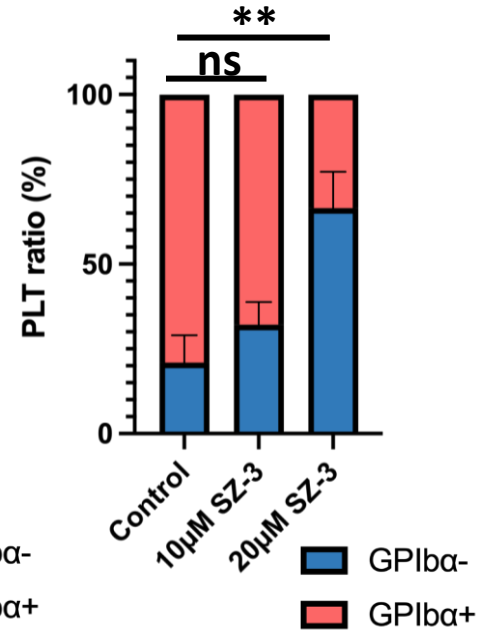
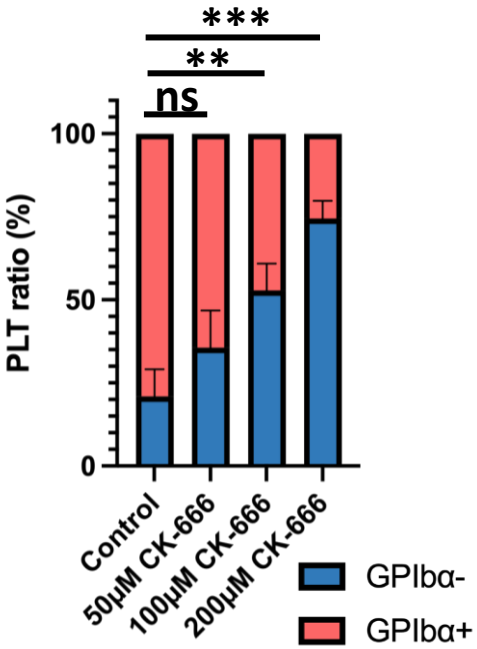
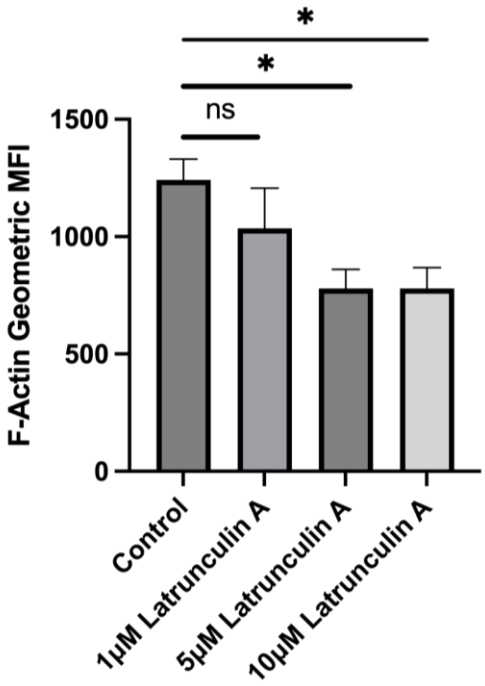


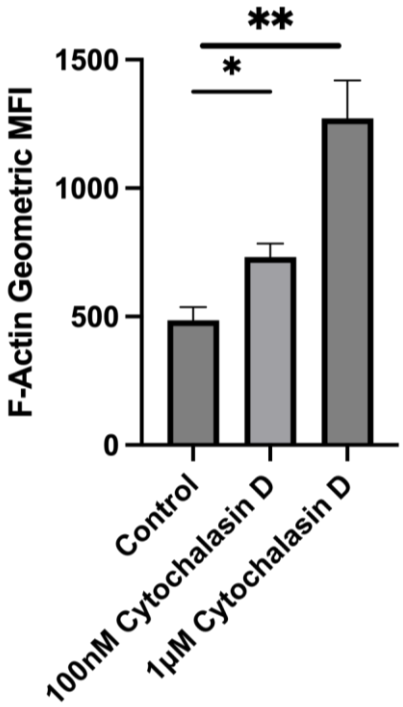
J



K


*
*
ns
1500
1000
500
0
F-Actin Geometric MFI
Control
1μM Latrunculin A
5μM Latrunculin A
10μM Latrunculin A

L


**
*
1500
1000
500
0
F-Actin Geometric MFI
Control
100nM Cytochalasin D
1μM Cytochalasin D

M

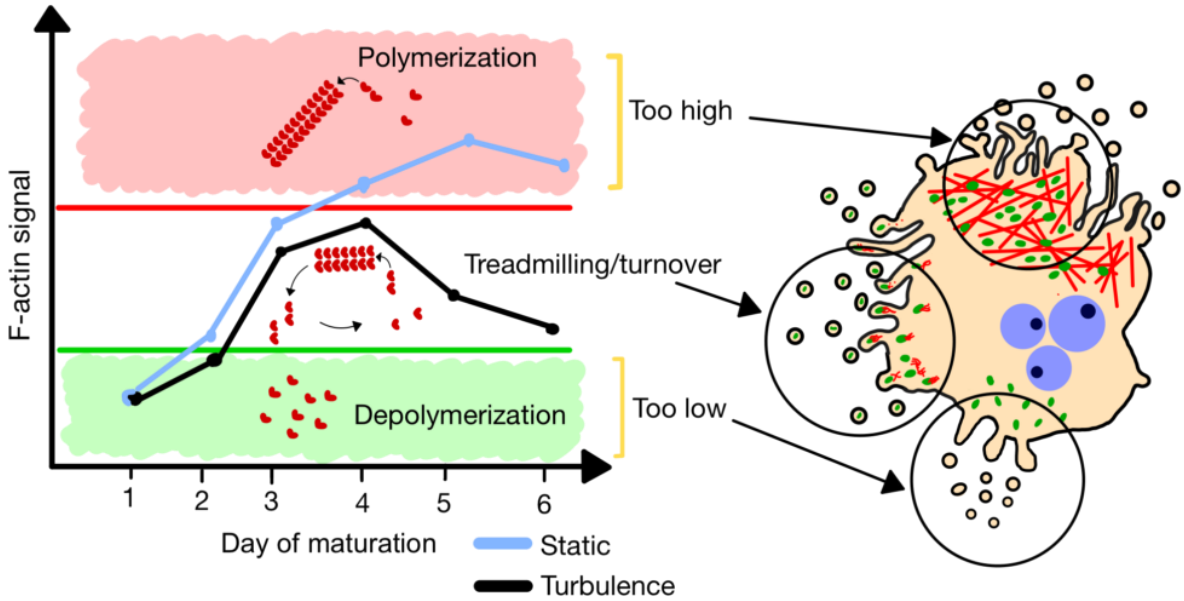
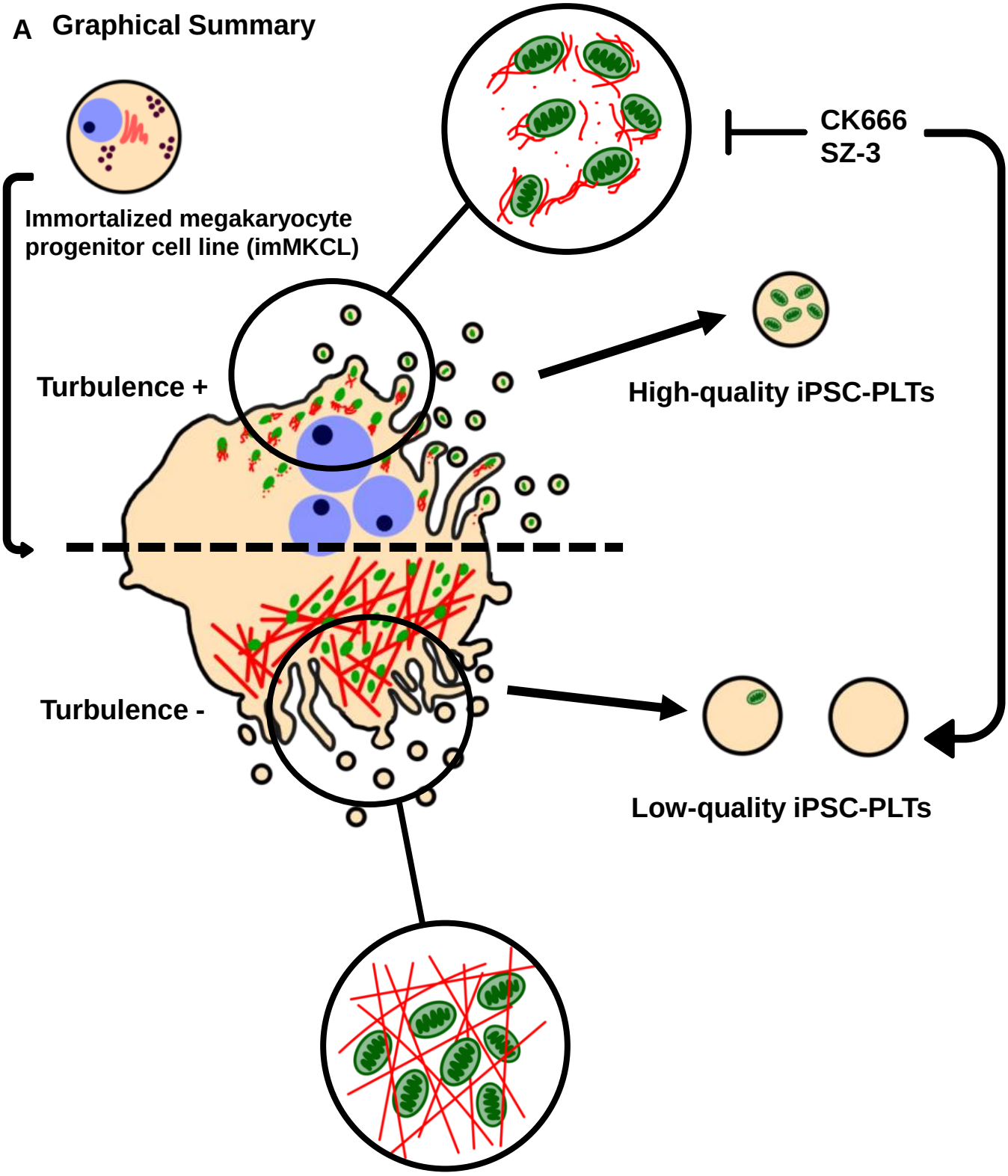

Polymerization
Too high
Treadmilling/turnover
Too low
Depolymerization
F-actin signal
1
2
3
4
5
6
Day of maturation
Static
Turbulence

Figure 6


A Graphical Summary
Immortalized megakaryocyte progenitor cell line (imMKCL)
CK666
SZ-3
Turbulence +
High-quality iPSC-PLTs
Turbulence -
Low-quality iPSC-PLTs