GPCR-dependent spatiotemporal cAMP generation confers functional specificity in cardiomyocytes and cardiac responses

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Abstract
Cells interpret a variety of signals through G protein-coupled receptors (GPCRs), and stimulate the generation of second messengers such as cyclic adenosine monophosphate (cAMP). A long-standing puzzle is deciphering how GPCRs elicit different responses, despite generating similar levels of cAMP. We previously showed that GPCRs generate cAMP from both the plasma membrane and the Golgi apparatus. Here, we demonstrate that cardiomyocytes distinguish between subcellular cAMP inputs to cue different outputs. We show that generating cAMP from the Golgi by an optogenetic approach or activated GPCR leads to regulation of a specific PKA target that increases rate of cardiomyocyte relaxation. In contrast, cAMP generation from the plasma membrane activates a different PKA target that increases contractile force. We validated the physiological consequences of these observations in intact zebrafish and mice. Thus, the same GPCR regulates distinct molecular and physiological pathways depending on its subcellular location despite generating cAMP in each case.

Introduction
G protein coupled receptors (GPCRs) are the largest family of membrane receptors that communicate downstream signaling pathways to regulate cellular functions. Many of them signal through the stimulatory G protein (Gs) to generate cyclic adenosine monophosphate (cAMP)[1]. There are a number of different hormones that stimulate cAMP generation through the activation of different types of GPCRs that are expressed in one cell [2,3]. However, activation of each GPCR can trigger different physiological responses despite generating the same level of cAMP. A classic example of such distinct physiological responses is the activation of beta-adrenergic receptors (βARs) and prostaglandin E1-type receptors, which trigger similar elevations of cAMP in cardiac tissue, but only the activated βAR is able to increase the contractility and glycogen metabolism in cardiomyocytes[4-7]. Analogous observations have been reported even within the same family of receptors. There are two main βAR isoforms in cardiomyocytes.

β1AR and β2AR are both activated by sympathetic hormones (epinephrine/ norepinephrine) and trigger cAMP generation; however, they elicit distinct effects on cardiac function. In healthy cardiomyocytes, β1AR signaling regulates chronotropy (heart rate), inotropy (force of contraction), and lusitropy (relaxation) [8-10]. In contrast, cAMP-mediated β2AR signaling only modestly affects chronotropy and does not affect lusitropy[11]. In heart failure, β1AR and β2AR function differently: β1AR signaling promotes cardiomyocyte hypertrophy and apoptosis, whereas β2AR signaling inhibits both [8,10-14]. Numerous hypotheses have been advanced to explain how β1AR and β2AR function differently from each other, both in health and disease states, but answers have been elusive. Importantly, β1AR and β2AR localize to different subdomains in cardiomyocytes. While β1AR is mostly at the plasma and Golgi membranes, β2AR is mostly localized in transverse-tubules (t-tubule)[15,16]. Whether this distinct receptor localization confers specificity on their function has not been addressed. In the past decade, several reports have shown that GPCR can signal from subcellular membrane compartments [17-25]. For example, we have shown that β1AR can be activated and generate cAMP from the plasma membrane and the Golgi apparatus [19], whereas β2AR can generate cAMP responses from the plasma membrane and endosomes[26]. The significance of generating cAMP from two distinct membrane compartments is just beginning to be understood. There is evidence that they might regulate distinct transcriptional responses [27,28] or activate distinct signaling pathways [16,29,30].

Classically, cAMP was considered a highly diffusible molecule, and thus it was reasoned that cAMP generation at the plasma membrane, by GPCR/Gs activation, is sufficient to activate downstream effectors of cAMP in other subcellular membrane compartments. Recent reports, however, demonstrate that cAMP is mostly immobile and constrained due to binding to specific cAMP binding sites. Several studies have reported the role of phosphodiesterases (PDEs) and the regulatory subunit of protein kinase A (PKA), the main cAMP binding protein, in constraining cAMP at specific membrane compartments [31-34]. In the basal state, cAMP was shown to be mostly bound to intracellular cAMP binding sites, such as PKA regulatory subunits, at each subcellular location and PDEs can generate a nanometer-size domain around a source of cAMP[35,36]. Moreover, the PKA regulatory subunit has been shown to form a liquid-liquid phase in the cytoplasm and sequester cAMP, thereby acting as a sponge to buffer cAMP in the cytoplasm[37]. It is only after the elevation of cAMP in cells, that free cAMP can act on PKA and other effectors to initiate downstream cellular responses. Furthermore, the catalytic activity of PKA has also been shown to be constrained to targets within a radius of 15-25 nm [38]**.** How this spatially and functionally restricted PKA can phosphorylate downstream targets localized within the cells is unclear. Thus, the nanometer scale of the cAMP diffusion range is in conflict with the prevalent model whereby plasma membrane-localized receptors generate cAMP which then propagates linearly to activate cAMP-mediated PKA responses in distant subcellular locations[34,39,40].

The present study reveals the pivotal role of local generation of cAMP in controlling local PKA activation at specific subcellular compartments. We demonstrate how cells with

more complex architecture, such as cardiomyocytes, are able to precisely sense subcellular cAMP pools and regulate local PKA activity to generate compartment-specific cellular and physiological outputs.

To determine the relevance of local cAMP generation and the activity map of cAMP around activated β1AR at distinct membrane locations, we measure the activation of downstream effectors of cAMP/PKA in cardiomyocytes. Using an optogenetic approach, we show that local generation of cAMP at the Golgi leads to distinct activation of downstream effectors of PKA that increases the rate of relaxation in cardiomyocytes. Conversely, we demonstrated that activation of the plasma membrane pool of β1AR, using pharmacological and genetic approaches, leads to the activation of proximal PKA effectors at the plasma membrane that increase the force of contraction in cardiomyocytes. Finally, we tested two different animal models, zebrafish and mice, using optogenetic and pharmacological approaches and found distinct regulation of cardiac inotropy and lusitropy by different cAMP pools.

Result

An optogenetic system to generate cAMP at the Golgi membrane in cardiomyocytes

To assess whether cAMP generation from the Golgi membrane communicates different cellular information, we developed an optogenetic system based on a bacterial photo-activatable adenylyl cyclase (bPAC). bPAC had been previously used to generate cAMP from distinct cellular compartments such as endosomes and cilia[28,41]. We fused bPAC to the trans Golgi Network 46 protein, a known Golgi-targeting motif, to target bPAC to the trans Golgi membrane in cardiomyocytes (Figure 1A and B). Golgi-bPAC generates cAMP in a dose-dependent manner in response to different blue light exposure times (Figure S1A). To assess whether cardiomyocytes expressing Golgi-bPAC generate cAMP in response to blue light treatment, we virally transduced cardiomyocytes and measured cAMP concentrations. Treating the cells with 0.34 $\mu W/cm^2$ blue light for 3 min results in 10-15 pmol/mg cAMP accumulation in cardiomyocytes (Figure 1C). This is consistent with the physiological level of cAMP in cardiomyocytes in response to β1AR stimulation with 100nM epinephrine (Figure S1B). Considering that the average volume of cardiomyocytes is reported at around 15pmol ($15000\mu m^3$)[42], this concentration translates into ~ 1μM cAMP in each cell, which is within the physiological levels of cAMP upon hormone stimulation [35,43].

Since cAMP generated from activated β1AR results in the activation of PKA in cardiomyocytes, we investigated whether cAMP generation from the Golgi membrane is able to activate downstream targets of PKA. In cardiomyocytes, β1AR-mediated cAMP generation regulates chronotropy (heart rate), inotropy (force of contraction), and lusitropy (relaxation) through PKA-mediated phosphorylation of proteins, such as cardiac Troponin I (TnI), Ryanodine 2 receptors (RyR2), and phospholamban (PLB) (Figure 1A)[8]. Thus, we examined whether generating physiological levels of cAMP by Golgi-bPAC can phosphorylate and activate downstream targets of PKA. Golgi-bPAC expression in the

absence of blue light had minimal effect on the phosphorylation of PKA effectors (Figure 1D, left lanes). Notably, 0.34 $\mu W/cm^2$ blue light treatment resulted in the robust phosphorylation of PLB but not TnI and RyR2 (Figure 1D middle lane and quantification in E). This suggests that cardiomyocytes may distinguish Golgi-cAMP at the physiological level, even without physical barriers to its intracellular movements in the cytoplasm.

We then explored whether supraphysiological cAMP levels can overcome this differential interpretation of cAMP from the Golgi membrane. To test this, we increased the blue light treatment to 3.2 $\mu W/cm^2$ and found that increasing cAMP generation from the Golgi membranes results in the phosphorylation of all three effectors (Figure 1C and 1D, right lanes and quantification in E). These results suggest that differential interpretations of cAMP generated at the Golgi can be saturated by supraphysiological concentrations of cAMP.

Given that PLB is a sarco/endoplasmic reticulum (SR)-localized protein and is the dominant regulator of Ca^{2+} reuptake by sarco/endoplasmic reticulum Ca^{2+} ATPases (SERCA)[44], we wondered whether local pool of cAMP, generated by Golgi-bPAC, phosphorylates PLB in the vicinity of the Golgi membrane. Immunofluorescence imaging of the non-phosphorylated form of PLB revealed an SR-localization pattern throughout the cytoplasm, as expected (Figure 1F, third row). When cardiomyocytes were stimulated with 0.34 $\mu W/cm^2$ blue light for 3min, immunofluorescence imaging of phosphorylated PLB showed immunostaining in the vicinity of the Golgi membranes (Figure 1F, bottom row). No-immunostaining was detected for the phosphorylated form of Tn-I and RyR2 at this blue light stimulation (Figure 1F, top rows). Together, these data suggest that cAMP generation from the Golgi membranes, similar to the level generated by the hormone-mediated cAMP response, results in PKA-mediated phosphorylation of downstream target, PLB, in the vicinity of the Golgi membrane.

Golgi-cAMP specifically regulates cardiomyocyte relaxation in zebrafish

As PLB is the key regulator of cardiomyocyte relaxation (lusitropy), we predicted that cAMP generation at the Golgi specifically regulates lusitropy. To test this hypothesis, we generated a Golgi-bPAC expressing transgenic zebrafish. The zebrafish is a well-established animal model for exploring the physiological parameters of cardiac function. The molecular mechanisms underlying their heart function are very similar to those of higher vertebrates[45]. The optical clarity of zebrafish embryos allows the real-time and in vivo visualization of the heart contractility responses and makes it an optimal vertebrate model system for studying cardiovascular performance using optogenetic tools [46,47]. To measure cardiac outputs such as chronotropy, inotropy, and lusitropy, we generated transgenic zebrafish that express Golgi-bPAC (Figure 2A). Treating Golgi-bPAC expressing zebrafish with 4.2 $\mu W/cm^2$ blue light resulted in cAMP generation at different time points (Figure 2B). These transgenic zebrafish were developed from the established line, Tg(Flk-Ras-cherry)^{s896}, which expresses Ras-Cherry in the inner layer of the heart wall (endocardium)[48]. As a result, we were able to trace the motion of the walls of the cardiac atrium (A) and ventricle (V) in different phases of the cardiac cycle in the RFP

channel using a confocal microscope imaging mCherry (Figure 2C). The coupling of ventricular and atrial contraction can be determined by evaluating the time delay between the peak values of the extracted synchronous chronologies within the same cardiac cycle (Figure 2D). Stimulating control fish (Tg(Flk-Ras-cherry)^{s896}) with 4.2 μW/cm^2 blue light at 1,3 and 5 min did not result in significant changes in the rate of contraction or relaxation (Figure S2). Treating Golgi-bPAC expressing zebrafish with 4.2 μW/cm^2 blue light for 3 min resulted in a significant increase in the rate of relaxation (lusitropy) but had no significant effect on the rate of contraction (inotropy) (Figure 2E). As more cAMP accumulated at 5 min after blue light stimulation, the rate of contraction and relaxation increased equally. This result is consistent with the specific phosphorylation of PLB but not TnI and RyR2 in cardiomyocytes using low-level blue light treatment. Treating Golgi-bPAC zebrafish with 4.2 μW/cm^2 blue light and the phosphodiesterase (PDE) inhibitor, 3-isobutyl-1-methylxanthine (IBMX), to increase cAMP levels and promote the cAMP diffusion throughout the cardiomyocytes, elevated the rate of both inotropy and lusitropy at all time points (Figure 2E). Thus, cAMP generation from the Golgi at the physiological level specifically regulates the rate of cardiac relaxation responses. However, this differential interpretation of cAMP is disrupted when local cAMP generation at the Golgi is increased to supraphysiological levels.

Plasma membrane and Golgi pools of β1-adrenergic receptors function differently

If Golgi-generated cAMP specifically regulated PLB phosphorylation and lusitropy, we hypothesized that hormone-mediated cAMP responses by Golgi-localized GPCR should regulate cAMP-mediated PLB phosphorylation. Similarly, the plasma membrane-localized GPCR likely regulates downstream effectors in the vicinity of the plasma membrane. To test this hypothesis, we studied the β1AR, a GPCR localized at the plasma membrane and the Golgi membranes in neonatal and adult cardiomyocytes (Figure 3A and S3). We have previously reported that both pools of receptors are capable of promoting cAMP generation [16,19]. In healthy cardiomyocytes, β1AR signaling regulates cardiac responses through PKA-mediated phosphorylation of proteins such as TnI, RyR2, and PLB (Figure 3B) [8]. Immunofluorescence imaging of the phosphorylated forms of RyR2, TnI, and PLB upon 10μM epinephrine stimulation showed a distinct localization pattern in cardiomyocytes. While phosphorylated PLB, localized near the perinuclear/Golgi membranes (Figure 3C and D), phosphorylated TnI and RyR2 localization did not colocalize with the Golgi marker and showed a plasmalemma and near t-tubule localization pattern, respectively (Figure 3E-H). Based on this distinct localization pattern, we hypothesized that β1AR-mediated cAMP likely regulates distinct PKA effectors in each membrane compartment's vicinity.

To assess whether the plasma membrane and Golgi pools of β1AR regulate different PKA effectors, we pharmacologically blocked β2AR with 10μM ICI118551 to specifically test the function of β1AR in cardiomyocytes. We took advantage of membrane-permeant and impermeant agonists of β1AR to compare the functions of plasma membrane and Golgi-localized β1AR in adult cardiomyocytes (Figure 4A). We have previously demonstrated that epinephrine, a membrane impermeant βAR agonist, requires a

monoamine transporter, an organic cation transporter 3 (OCT3), to reach the Golgi lumen and activate Golgi-localized β1AR[19]. OCT3 is highly expressed in cardiomyocytes (Figure S4B)[49]. Pharmacological inhibition of OCT3 inhibits epinephrine/norepinephrine-mediated Golgi-localized β1AR activation[16,19]. Importantly, OCT3 inhibition abolishes epinephrine-mediated phosphorylation of PLB but not β1AR-mediated phosphorylation of TnI and RyR2 (Figure 4A and B). Unlike epinephrine, dobutamine, a membrane-permeable β1AR agonist, can activate Golgi-localized β1AR independently of OCT3 (Figure 4A and B). Similarly, cardiomyocytes derived from OCT3 knock-out mice that show similar expression of β1AR (Figure S4A) showed no changes in PLB phosphorylation upon epinephrine stimulation but an increase in TnI and RyR2 phosphorylation. In contrast, dobutamine can still activate the Golgi-localized β1AR and increase PLB phosphorylation (Figure SC-D). Thus, our results indicate that plasma membrane-localized β1AR regulates TnI and RyR2 phosphorylation to control inotropy (contraction), whereas Golgi-localized β1AR specifically regulates PLB phosphorylation to control lusitropy (relaxation).

β1AR autoantibodies specifically activate plasma membrane-localized β1AR and regulated cardiomyocytes contractility

To further distinguish the roles of Golgi and plasma membrane-β1AR signaling in regulating cardiomyocyte contractility, we took advantage of an autoantibody against β1AR to specifically activate β1ARs only at the plasma membrane (Figure 4C). Autoantibodies against β1ARs have been reported in various cardiac diseases, including dilated cardiomyopathy[50-52]. Many of these autoantibodies function as agonists because their epitope sequences have sequence similarities to the extracellular loop 2 of β1ARs[52]. Previous studies have shown a measurable cAMP production and positive inotropic response upon treating cardiomyocytes with autoantibodies[53,54]. Given that antibodies are membrane impermeant and cannot cross the plasma membrane, we used them to activate the plasma membrane pool of β1AR specifically. Stimulating isolated cardiomyocytes with various concentrations of the antibody, generated against extracellular loop 2 of β1AR, increased RyR2 phosphorylation but did not affect PLB and TnI phosphorylation (Figure 4E and F). These data further support a model where different pools of β1ARs regulate distinct functions in cardiomyocytes, with Golgi-localized-β1ARs regulating PLB phosphorylation and the plasma membrane-localized β1ARs regulating RyR2 phosphorylation. Interestingly, we did not observe TnI phosphorylation by the β1ARs autoantibody. The inability of the autoantibody to induce phosphorylation of PKA targets (PLB and TnI phosphorylation) outside of the dyadic cleft further support the lack of cAMP diffusion from its source of generation. Moreover, these functional data along with our β1ARs immunostaining data suggest that β1AR has a distinct localization pattern on the plasma membrane of cardiomyocytes and is concentrated in the t-tubules, an invaginated region of the plasma membrane that is near the SR junctional region (dyadic cleft) where RyR2 is localized (Figure S3).

Plasma membrane and Golgi PKA have distinct functions

PKA is a holoenzyme composed of two regulatory (PKA-R) and two catalytic (PKA-C) subunits anchored to membranes by A-kinase anchoring proteins. As a result, PKA holoenzymes are highly compartmentalized[55 33,39,56]. It was commonly believed that the PKA-C subunit dissociates from the PKA-R subunit in the presence of excess cAMP, and thus PKA-C can activate downstream effectors localized within the cells [57,58]. However, recent studies have revealed that the activity of the PKA-C subunit is constrained to targets within a radius of 15-25 nm [38]. Given that this spatially and functionally restricted PKA can only phosphorylate proximal downstream targets in cardiomyocytes, it stands to reason that the plasma membrane-localized receptors are unlikely to be the sole source of cAMP-mediated PKA activation. To test which pool of PKA within the cells regulates the phosphorylation of downstream effectors, we targeted a dominant-negative PKA (dnPKA), a constitutively repressive version of PKA-RIa that is insensitive to cAMP [59,60] to the plasma membrane (PM-dnPKA) (Figure 5A). To target dnPKA to the plasma membrane, we fused it to the CAAX motif of the K-Ras protein. PM-dnPKA was localized on both plasmalemma of the plasma membrane and thin parallel striation that colocalized with sarcomeric z-disk markers (α-actinin), a membrane region in cardiomyocytes that closely coincides with t-tubules (Figure 5B). We then assessed how the inhibition of the plasma membrane pool of PKA affects epinephrine-mediated phosphorylation of downstream PKA targets in cardiomyocytes. Stimulation of cardiomyocytes with epinephrine results in the phosphorylation of RyR2, TnI, and PLB. Interestingly, epinephrine-stimulated cardiomyocytes expressing PM-dnPKA show abrogated RyR2 phosphorylation, but TnI and PLB phosphorylation remained unchanged (Figure 5C-F). Thus, we concluded that plasma membrane-localized β1AR specifically regulates PKA-mediated RyR2 phosphorylation. These data, along with our findings using autoantibodies (Figure 4C-E), further confirm that the plasma membrane-β1AR, most likely concentrated in the t-tubules, is distinctly activating PKA at the t-tubule, and then regulating RyR2 near the SR junctional regions.

OCT3 knock out mice have preserved inotropy but delayed lusitropy

Increased sympathetic activity during the fight and flight response or exercise causes an increase in epinephrine/norepinephrine levels in the circulation and enhances βARs activity. Thus, the heart efficiently augments cardiac output by increasing the heart rate, dromotropy (conduction speed), inotropy (force of contraction), and lusitropy (rate of relaxation). Our data in isolated adult and neonatal cardiomyocytes suggest that plasma membrane-localized β1AR regulates RyR2 phosphorylation, a key Ca^{2+} channel that increases the release of Ca^{2+} from SR, and thus triggers the cardiac muscle to contract. In contrast, we found that Golgi-localized β1AR specifically regulates PLB phosphorylation, a key regulator of Ca^{2+} reuptake to the SR through SERCA Ca^{2+} channels, thus promoting cardiac muscle relaxation (Figure 4 and 5). These data suggest that plasma membrane β1AR regulates inotropy whereas Golgi-localized β1AR regulates lusitropy. To test this hypothesis, we performed real-time measurements of pressure and volume (PV loop) within the left ventricle of the mice in response to bolus injections of epinephrine (Figure 6A). Several physiologically relevant hemodynamic parameters, such as stroke volume, ejection fraction, myocardial contractility, and lusitropy, can be

determined from these loops (Figure 6B). To measure the PV loop upon stimulation of βARs, we inserted a 1.4-F pressure-conductance catheter (Millar Instruments, Houston, TX) and injected mice at the right jugular vein with 10μg/kg epinephrine. To isolate the function of the plasma membrane and Golgi-localized β1AR, we compared wild-type and OCT3 knock-out mice (Figure S4A and B) [61]. Given that OCT3 facilitates the transport of epinephrine to the Golgi-localized β1AR and OCT3 inhibition leads to abrogated PLB phosphorylation in cardiomyocytes (Figure 4A-B), we predicted that OCT3 knock-out mice will have delayed lusitropic response. Epinephrine injection induced an increase in the heart rate of both wild-type and OCT3 knock-out mice (Table 1). Importantly, the maximal rate of left ventricle pressure change (dp/dt max), ejection fraction, and cardiac output, which are the key indications of systolic function of contraction (inotropy), were similar upon epinephrine injection between the wild-type and OCT3 knock-out mice (Figure 6C and Table 1). An increase in contractility is observed as an increase in dP/dt max during isovolumic contraction. Thus, these data suggest that wild-type and OCT3 knock-out mice have a similar rate of contraction upon epinephrine injection. However, the minimal rate of left ventricle pressure change (dp/dt min), which is manifested as an increase in diastolic function or an increase in the rate of relaxation (lusitropy), was delayed in OCT3 knock-out mice (Figure 6D). Moreover, tau, which represents the exponential decay of the ventricular pressure during isovolumic relaxation, was also delayed in OCT3 knock-out mice compared to wild-type (Figure 6E). Importantly, dobutamine injection, a membrane-permeant β1AR agonist that does not require OCT3 to activate Golgi-localized β1AR[16,19], caused similar increases in the rate of contraction, relaxation, and tau in both wild-type and OCT3 knock-out mice (Figure 6 C-E). Altogether, these data suggest that OCT3 knock-out mice have preserved systole (inotropy) but delayed diastole (lusitropy).

Discussion

Our findings demonstrate the cellular and physiological significance of cAMP generation at specific locales. We present evidence that cells with more complex architecture, such as cardiomyocytes, distinguish local cAMP generation and cue different physiological outputs. We demonstrated that localized activation of β1ARs at various internal compartments leads to local generation of cAMP and activates downstream PKA effectors that are in each compartment's vicinity. Using an optogenetic approach, bPAC, we show that cAMP generation at the Golgi results in PLB phosphorylation and consequently increases the rate of relaxation in cardiomyocytes, an observation verified in the intact hearts of zebrafish. Furthermore, we found that the plasma membrane pool of cAMP regulates local PKA effectors, such as RyR2, leading to an increase in the contractile force. Importantly, we showed that a monoamine transporter (OCT3) that facilitates the transport of epinephrine/norepinephrine regulates the activation of Golgi-β1AR-mediated PLB phosphorylation. Thus, epinephrine stimulation in OCT3 knock-out cardiomyocytes only activates the β1AR pools at the plasma membrane. This observation was further verified in OCT3 knock-out mice, where the force of contraction (systole) was preserved upon epinephrine injection, but the relaxation rate (diastole) was impaired.

Examining the publicly available phenotype across >420,000 individuals in UK Biobank with exome sequencing data shows that loss of function OCT3 (SLC22A3) is significant associated with cardiovascular diseases, specifically diastolic pressure[62]. Recently, it was shown that several prescription drugs that potently inhibit OCT3 cause adverse reactions related to cardiovascular traits[63]. The findings from this study suggest the possibility that these adverse reactions may be due to alterations in subcellular cAMP/PKA signaling caused by inhibition of OCT3.

Our data using an antibody against the extracellular loop 2 of β1AR to specifically activate the plasma membrane-pool of β1AR supports the notion that β1AR is mainly concentrated at the t-tubule near the SR junction region where RyR2 is localized. Thus, generating cAMP by plasma membrane-pool of β1AR resulted in the phosphorylation of RyR2 and had no effect on PLB and TnI phosphorylation found in the none-junctional SR regions and myofilaments, respectively. Accordingly, inhibiting PKA at the t-tubules, abrogates epinephrine-mediated RyR2 phosphorylation but has no significant effect on TnI and PLB phosphorylation. These findings suggest that the functional pool of β1AR/cAMP/PKA resides in the t-tubules, near the SR junctional region, thus regulating the increase in the contractile force of cardiomyocytes. The β1AR autoantibodies are present in more than 30% of patients with dilated cardiomyopathy. It has been reported that these autoantibodies function as an agonist and specifically induce a positive inotropic effect, one of the key manifestations of increased contractile force[54]. Thus, our data provide a mechanistic explanation for the increased inotropy observed in patients with dilated cardiomyopathy.

There are a number of different genetically encoded membrane-localized fluorescence and bioluminescence-based biosensors that have been developed to study cAMP compartmentalization[64-67]. Almost all of these studies focused on the role of PDEs, AKAPs, and PKA in forming cAMP domains at different subcellular compartments but assumed the sole source of cAMP to be generated by activated GPCRs on the plasma membrane. Previous views of localized-GPCR signaling have been mainly attributed to receptor-associated cAMP micro- or nanodomain localization on the plasma membrane. For instance, it has been shown that β2ARs, but not β1ARs, are exclusively associated with caveolae and lipid rafts[68-70]. Thus, it was thought that the distinct signaling functions of β1AR and β2AR are due to their unique localization on the plasma membrane[68,71-80]. More recently, the cAMP nanodomain formation on the plasma membrane has been reported for glucagon-like 1 peptide receptor and β2AR where signaling specificity is determined based on the formation of receptor-associated cAMP nanodomains on the plasma membrane [36]. The significance of GPCR signaling at subcellular locations other than the plasma membrane has only recently been explored. Nash *et al* have demonstrated that inhibition of OCT3 abrogates β1AR-mediated Epac-dependent phospholipase Cε activation and hydrolysis of phosphatidylinositol-4-phosphate, a signaling pathway that contributes to the hypertrophic responses. More recently, it has been reported that a pool of β1AR is associated with the SERCA2 complex and regulates calcium transients and contraction responses[29]. Our data here provide the first evidence

for the physiological significance of cAMP nanodomain formation by activated GPCRs on the plasma membrane and the Golgi membranes for regulating distinct cardiac function.

These novel insights on the significance of local cAMP signaling could have important implications for a better understanding of cardiac diseases. For instance, our PV-loop measurements of OCT3 knock-out mice mimic what is seen in diastolic dysfunction, a highly significant but poorly understood clinical condition where the cardiac muscle contraction is preserved, but relaxation is impaired. This is the first molecular manipulation that has recapitulated the phenotype seen in this disease. Thus, we believe that our data could provide a mechanistic window into understanding this major clinical issue. For instance, it may suggest that patients with preserved systole and impaired diastole could have aberrations in cAMP signaling from the Golgi caused by a reduced receptor pool at the Golgi, impaired expression and plasma membrane localization of OCT3, or reduced activity of downstream PKA effectors such as PLB. Establishing the physiological significance of GPCR/cAMP signaling from subcellular compartments in healthy cardiomyocytes is the first step in unraveling how this signaling specificity goes awry to cause cardiac disease.

Figure Legends:

Figure 1. cAMP generation at the Golgi distinctly regulate cardiomyocyte relaxation. **A.** Illustration of the roles of subcellular cAMP/PKA signaling hubs in regulating contraction/relaxation responses of cardiomyocytes. The cAMP/PKA signaling hub on the sarcolemma and t-tubule increase cardiac muscle contraction by promoting the phosphorylation of cardiac troponin I (cTnI), ryanodine receptor 2 (RyR2), and L-type calcium channel (LTCC). Activation of the Golgi pool of cAMP/PKA increases the phospholamban (PLB) phosphorylation to induce cardiac muscle relaxation by promoting sarcoplasmic reticulum Ca^{2+}-ATPase (SERCA)-mediated calcium uptake. After blue light (~450nm) stimulation, Golgi-targeting bPAC (TGNP-bPAC) produces cAMP to activate cAMP/PKA signaling near the Golgi membranes. **B.** Golgi-bPAC was generated by fusing the bPAC protein to the transmembrane and cytoplasmic domain of TGNP with a SNAP-tag. Representative images of Golgi-bPAC (red) and Golgi marker (green), visualized by SNAP and GM130 antibodies, and DAPI staining. Scale bar, 10 μm. **C.** cAMP generation mediated by Golgi-bPAC in neonatal cardiomyocytes. Cells were stimulated with blue light for 3 min or forskolin (FSK) for 5 min and then lysed for direct cAMP determination by ELISA. cAMP concentrations were normalized to the relative protein concentrations in each sample. The quantified data are represented as mean ± S.E.M. The p-values were calculated by one-way ANOVA. ns, not significant; $^{**}p<0.001$. **D.** Representative phosphorylation profiles of RyR2, TnI, and PLB induced by Golgi-bPAC in mouse neonatal cardiomyocytes. The protein levels of p-RyR2 Ser2808, p-TnI Ser23/24, and p-PLB Ser16/Thr17 were analyzed in the Golgi-bPAC-expressing mouse neonatal cardiomyocytes kept in the dark or exposed to 0.34 or 3.2 $\mu W/cm^2$ blue light for 3 minutes. The protein level of Golgi-bPAC was analyzed using the SNAP antibody. The protein level

of CSQ2 was used as a loading control. **E**. The band intensities of p-RyR2, p-TnI, and p-PLB were normalized to CSQ2 intensity and then transformed by the normalization with the highest value in the groups. The quantified data from different experiments are presented as mean ± S.E.M. The p-values were calculated by one-way ANOVA. $^{**}p<0.01$; $^{***}p<0.005$ and $^{****}p<0.0001$. n=6 biological replicates. **F.** The subcellular localization of p-RyR2, p-TnI, PLB, and p-PLB upon stimulation of Golgi-bPAC with 0.34 μW/cm^2 blue light in mouse neonatal cardiomyocytes. The protein localizations of p-RyR2 Ser2808, p-TnI Ser23/24, total PLB, and pPLB Ser16/Thr17 antibody were visualized (green) with Golgi marker stained by GM130 (red). Scale bar, 10 μm.

Figure 2. Golgi-delimited cAMP generation promotes faster ventricular relaxation in zebrafish. A. Representative agarose gel electrophoresis of wild-type (WT) and GalT-bPAC zebrafish genotyping. The plasmid for the Golgi-bPAC was cloned by fusing GalT, bPAC, myc, and m-cherry into a pminiTol2 plasmid. The plasmid was linearized and co-injected with transposase mRNA into the cell of a ZF embryo at the one-cell stage. GalT, bPAC, and mApple, were amplified from caudal fin samples to sort the transgenic fish. DRER is the DNA extraction and genotyping control for ZF samples. **B.** Golgi-bPAC zebrafish (72hpf) generate cAMP in response to blue light (4.2 μW/cm^2) in a time-dependent manner. Individual fish were lysed in 120 μL of 0.1M HCl, and then cAMP was detected by a direct determination ELISA assay. **C.** Left: Illustration of the mounting position of the zebrafish to image the heart. Middle: Diagram of the zebrafish heart. Right: Representative image of a live zebrafish heart. **D.** Representative images demonstrating ventricular contraction and relaxation in zebrafish. Fluctuations in the fluorescence of the heart during contraction and relaxation over time are measured. The time between fluorescence maxima to minima is the time of contraction, and the subsequent fluorescence minima to maxima portion of the graph is measured as the time of relaxation. **E.** Changes in Golgi-bPAC zebrafish contraction and relaxation from baseline. Basal images of the zebrafish hearts were acquired for 1500 frames. The transgenic Golgi-bPAC zebrafish were exposed to 4.2 μW/cm^2 blue light and imaged after 1, 3, and 5 min stimulation. The difference between baseline and stimulated contractility times are quantified and presented here as mean ± S.E.M. with p-values presented. Data were analyzed by a one-way ANOVA and Tukey's t-test. n=40-60 fish per condition.

Figure 3. Epinephrine stimulation of mouse neonatal cardiomyocytes reveals spatially distinct phosphorylation patterns of downstream PKA effectors. A. Representative images of β1AR(green) localization relative to TGN38 (trans-Golgi) and GM130 (cis-Golgi) in mouse neonatal cardiomyocytes. Endogenous β1AR is expressed on the plasma membrane and the Golgi membranes. Scale bar, 10 μm. **B.** Model of compartmentalized β1AR's regulation of PKA effectors. The organic cation transporter 3 (OCT3) facilitates the uptake of epinephrine/norepinephrine to the Golgi-localized β1AR. **C-H.** Representative images of epinephrine-mediated phosphorylation of PLB, TnI, and RyR2 in neonatal cardiomyocytes. Neonatal cardiomyocytes were incubated with epinephrine (10 μM) for 20 min and immune-stained for p-RyR2 Ser2808, p-TnI Ser23/24, or p-PLB Ser16/Thr17, and TGN38. Representative ROIs in the merged images were

analyzed by fluorescence line scan intensity and shown in the corresponding graphs (D, F, and H). The maximal fluorescence intensity of the PLB, TnI, and RyR2, relative to the Golgi markers, are measured along the width of the neonatal cardiomyocytes. The length of each ROI was normalized and organized into 100 bins; the average intensity of each bin is shown. These graphs demonstrate the phosphorylated proteins' localization, spread, and intensity throughout the cells. n=15 cells per condition.

Figure 4. Plasma membrane and the Golgi pools of β1AR function differently. A. Corticosterone (Cortico)-mediated inhibition of OCT3, the transporter that allows epinephrine to access the Golgi, blocks phosphorylation of PLB but not TnI and RyR2 in adult cardiomyocytes. Membrane permeable β1AR selective agonist, dobutamine (Dobut), promotes PLB phosphorylation independent of OCT3. Adult cardiomyocytes were pretreated with β2AR selective antagonist ICI-118551 (ICI) to isolate the function of β1ARs. Thus, Golgi β1AR regulates PLB phosphorylation, a mediator of cardiomyocyte relaxation. **B-D.** Quantification of immunoblots of p-RyR2 Ser2808, p-TnI Ser23/24, and p-PLB Ser16/Thr17 normalized to the protein level of CSQ2, transformed by the normalization with the highest value in the groups. The quantified data from different experiments were presented as mean ± S.E.M. The p-values were calculated by one-way ANOVA. *$p<0.05$; **$p<0.001$, ns, not significant. n=6 biological replicates. **E.** Model of the autoantibody (AAb)-mediated activation of plasma membrane-localized β1AR. The amino acid similarity between the second extracellular loop of β1AR and an AAb's epitope region (blue color labeled) found in patients with dilated cardiomyopathy (DCM). **F-G.** Representative western blots of RyR2, TnI, and PLB phosphorylation profiles regulated by β1AR AAb in mouse neonatal cardiomyocytes. Mouse neonatal cardiomyocytes were treated with β1AR AAb for 15 minutes. The protein levels of p-RyR2 Ser2808, p-TnI Ser23/24, and p-PLB Ser16/Thr17 were analyzed. The protein level of p-RyR2 was normalized with the protein level of CSQ2, then transformed by the normalization with the value from the FSK-treated group (10 μM). The quantified data from different experiments were presented as mean ± S.E.M. The p-values were calculated by one-way ANOVA. **$p<0.01$; ***$p<0.005$; ****$p<0.0001$. n=6 biological replicates.

Figure 5. Plasma membrane and the Golgi pool of PKA have distinct functions. A. Model of targeting a dominant-negative PKA (dnPKA) to the plasma membrane (PM-dnPKA) to local PKA activity in cardiomyocytes. PM-dnPKA was generated by fusing dnPKA with sfGFP and CAAX motif. PM-dnPKA, visualized by GFP (green), was co-stained with α-actinin (red), a marker of t-tubules, and DAPI. Insets show co-localization of PM-dnPKA to t-tubules. Scale bar, 10 μm. **C-D.** The representative western blots of RyR2, TnI, and PLB phosphorylation profiles regulated by epinephrine in the absence or presence of PM-dnPKA expression. The protein levels of p-RyR2 Ser2808, p-TnI Ser23/24, and p-PLB Ser16/Thr17 were analyzed in wild-type and PM-dnPKA-expressing moue neonatal cardiomyocytes without or with 0.1 μM epinephrine treatment for 15 minutes. The band intensities of p-RyR2, p-TnI, and p-PLB were normalized with CSQ2 intensity and then transformed by the normalization with the highest value in the groups. The quantified data from different experiments were presented as mean ± S.E.M. The p-

values were calculated by two-way ANOVA. **p<0.01, ***p<0.005, ****p<0.0001; ns, not significant. n=6 biological replicates.

Figure 6. Pressure-Volume measurement of OCT3 knock-out mice revealed preserved systole but impaired diastole. A. Diagram demonstrating the placement of the catheter for pressure-volume measurements in mouse hearts. The catheter (Millar Instruments) is inserted into the apex through a needle stab wound. The catheter has one pressure sensor and conductance electrodes which measure ventricular volume. **B.** Representative pressure-volume loop. Each loop shows the changes in pressure and volume during isovolumetric contraction, ejection, isovolumetric relaxation, and filling of the left ventricle. Shifts in the loops between basal and stimulated conditions can provide a comprehensive analysis of cardiac function and can be used to assess the heart's performance by quantitatively measuring hemodynamic parameters. Multiple cardiac indicators, including the end-systolic pressure-volume relationship (ESPVR), end-diastolic pressure-volume relations (EDPVR), stroke volume, cardiac output, and ejection fraction, can be derived from PV loops. **C.** Pressure volume (PV) loop experiments were performed on mice to determine the effect of Golgi-delimited signaling of the β1AR. We examine this using OCT3 (*SLC22A3*) knock-out mice to limit the access of epinephrine (cell-impermeable endogenous β1AR agonist) to the Golgi compared with dobutamine (cell-permeable selective β1AR agonist) treated mice. Wild-type and OCT3 (*SLC22A3*) knock-out mice were anesthetized, and an apical catheterization of the left ventricle was performed. Basal PV-loops were collected as a control for each mouse. Either epinephrine (10 μg/kg) or dobutamine (18.4 μg/kg) were administered by bolus injection through the jugular vein and repeated measurements of PV loops were collected. The maximum dP/dt is the derivative of pressure that increases over time and is a measurement of systolic function. **D.** The minimum dP/dt is the derivative of pressure that decreases over time and is an indicator of relaxation of the left ventricle. **E.** Tau represents the decay of pressure during isovolumetric relaxation that is preload independent. Data are presented as mean ± S.D. The p values were calculated by t-test. n=11 mice in each condition.

Figure S1. Golgi-bPAC stimulates cAMP generation in response to blue stimulation over time. A. Representative images of HeLa cells expressing Golgi-bPAC (left). Golgi-bPAC induces increasing cAMP generation upon blue light stimulation over time in HEK293 cells (right). **C.** Dose-response curve of cAMP generation in mouse neonatal cardiomyocytes upon various epinephrine concentrations.

Figure S2. Contraction and relaxation responses of Control Tg(Flk:Ras-cherry)s896 to blue light stimulation. Zebrafish were stimulated with 4.2 μW/cm^2 blue light for 1, 3, and 5 min and changes in time of contraction and relaxation were calculated. The quantified data are represented as mean ± S.E.M., p-values were calculated by paired two-tailed t-tests. n=11-18 fish.

Figure S3. Plasma membrane Golgi localization of β1AR in adult cardiomyocytes. Isolated adult cardiomyocytes from wild-type showed distinct t-tubule and Golgi

localization, as detected by β1AR (green) and TGN38 (red) (Golgi marker) antibodies. The distinct t-tubules and Golgi staining of β1AR are not detectable in adult cardiomyocytes isolated from β1AR/ β2AR double knock-out mice.

Figure S4. Epinephrine stimulation of adult cardiomyocytes derived from OCT3 (*SLC22A3*) knock-out mice does not promote phospholamban phosphorylation.
A. Representative agarose gel electrophoresis of wild-type and OCT3 (*SLC22A3*) knock-out hetero- and homozygotes mice genotyping. **B.** Western blot of OCT3 (*SLC22A3*), OCT1 (*SLC22A1*), β1AR and CSQ2 from wild-type and OCT3 (*SLC22A3*) knock-out-derived cardiomyocytes. **C.** Representative western blots of phosphorylation profiles of RyR2, TnI, and PLB regulated by β1AR in adult cardiomyocytes derived from OCT3 (*SLC22A3*) knock-out mice. **D-F**. Quantification of immunoblots of p-RyR2 Ser2808, p-TnI Ser23/24, and p-PLB Ser16/Thr17 normalized to the protein level of CSQ2, transformed by the normalization with the highest value in the groups. The quantified data from different experiments were presented as mean ± S.E.M. The p-values were calculated by one-way ANOVA. *$p<0.05$; ns, not significant. n=3 biological replicates.

Material and Methods

Reagents and antibodies

Human insulin, human transferrin, and sodium selenite (ITS), urethane, 2,3-Butanedione monoxime (BDM), Taurine, protease XIV, polybrene, forskolin, epinephrine, dobutamine, corticosterone, and IBMX are from Sigma. Glutamax solution, Penicillin and Streptomycin, HEPES buffer, HBSS buffer, M199 medium, ultrapure H_2O, Dulbecco's minimal essential medium (DMEM), mouse laminin, and Halt™ protease and phosphatase inhibitor cocktail are from Thermo Fisher Scientific. Fetal bovine serum (FBS) and Nu serum IV are from Corning. Glucose, sodium chloride, potassium chloride, sodium phosphate monobasic monohydrate, magnesium chloride hexahydrate, Tris-base, K-pipes, HEPES, EDTA, DTT, DMSO, and Tween-20 are from Fisher Bioreagents. Calcium chloride, Trolox, and tricaine are from Acros Organics. ICI-118551 are from TOCRIS. Doxycycline is from Takara. Heparin solution is from Fresenius Kabi. Collagenase II is from Worthington. Bovine serum albumin (BSA) and dry milk powder is from Research Product International. EGTA is from Alfa Aesar. Triton X-100 is from Bio-Rad. Proteinase K is from Roche. Rabbit anti-phospho phospholamban (Ser16/Thr17) antibody (#8496) and rabbit anti-phospho troponin I (Ser23/24) antibody (#4004) are from Cell Signaling. Rabbit anti-phospho ryanodine receptor 2 (Ser2808) antibody (#PA5-104444) is from Thermo Fisher Scientific. Rabbit anti-Calsequestrin 2 antibody (#18422-1-AP) and Rabbit anti-SLC22A1 antibody (#24617-1-AP) are from Proteintech. Rabbit anti-SLC22A3 antibody (#ab183071) and rabbit anti-β1AR (#ab3442) are from Abcam. Rabbit anti-SNAP tag antibody (#P9310S) is from New England BioLabs. Mouse anti-GM130 is from BD Biosciences (#610822). Sheep anti-TGN38 is from Bio-Rad (#AHP499G). Mouse anti-α-actinin is from Sigma (#A7811).

Plasmid construction

To generate pLVXTetOne_signal peptide (SS)-SNAP-TGNP-bPAC plasmids, DNA fragments of SS-SNAP were amplified from pcDNA3_SS-SNAP-ADRB2 (a gift from Dr. von Zastrow lab). The fragments of bPAC and TGNP were amplified from cytoplasmic-bPAC (a gift from Dr. Reiter lab) and pmApple-TGNP-N-10 (Addgene plasmid #54954), respectively. To generate pLVXTetOne_dnPrkar1a-msfGFP-CAAX, the DNA fragments of dnPrkar1a, msfGFP, and CAAX were cloned from pCS2+_dnPKA-GFP (a gift from Randall Moon, Addgene #16716), msfGFP containin plasmid (a gift from Dr. Giacomini lab), and pHR_SFFVp-CIB-GFP-CAAX (a gift from Dr. Weiner lab). The cloned DNA fragments were inserted into the pLVXTetOne lentiviral vector (a gift from Dr. Jura lab). To generate the pminiTol2 cmlc2: GalT-bPAC, the bPAC was amplified from cytosolic bPAC (a gift from Dr. Reiter lab), GalT and mApple were amplified from the FKBP-GalT-mApple plasmid[19], and inserted into the pminiTol2 cmlc2 vector (a gift from Dr. Von Zastrow lab).The DNA fragments were amplified by Pfu Ultra II Hotstart PCR master mix (Agilent Technologies) and ligated with each respective vector by NEBbuilder HiFi DNA assembly master mix (New England BioLabs).

Cell culture and lentivirus production

HEK293, HeLa, and HEK293T cells are cultured in DMEM (#11965092) containing 10% FBS. Lentiviral vector was co-transfected with pSPAX2 and pMD2.G plasmids (gifts from Dr. Julius lab) to HEK293T by TransIT-Lenti transfection reagent (Mirus Bio). The lentivirus was produced in DMEM containing 10% FBS and 1% BSA and then concentrated by the Lenti-X concentrator (Takara Bio).

Animals

CD-1, wild-type C57BL/6, *Slc22a3*-null C57BL/6, and *Adrb1*^{tm1Bkk} *Adrb2*^{tm1Bkk}/J mice (#003810) were housed in the facilities controlled by standardized environmental parameters, including a 12-hour light/dark cycle in 7 days per week, humidity 30-70%, temperature 20-26°C, and access to water and foods *ad libitum*. All animal experiments were approved by the Institutional of Animal Care and Use Committee of the University of California, San Francisco. Genotyping of wild-type and *Slc22a3* null alleles were performed as previous described[81]. The primer sets for the genotyping are: wild-type allele (F: 5'-gttctggcctaggcagtgcctctaat-3' and R: 5'-gtgctaatgacaacacatggagatg-3'; 300bp) and Slc22a3-null allele (F: 5'-ggtactattcctcttgccaatcc-3' and R: 5'-gtgctaatgacaacacatggagatg-3'; 500bp). Genotyping of *Adrb1*^{tm1Bkk} *Adrb2*^{tm1Bkk}/J mice was performed based on the protocols and primer information on The Jackson Laboratory website. Genotyping was performed using GoTaq Green master mix (Promega).

Zebrafish were reared and handled in compliance with standard laboratory practices and IACUC protocols. Embryos were maintained in egg water at 28°C in the dark for 5 days, and then raised in a 14 h light/ 10 h dark cycle. Experimental embryos were assayed within 72hpf at which time sex cannot be easily identified. However, sex is unlikely to affect the signaling pathways and physiological outputs in this study. GalT-bPAC fish were generated through the Tol2 transposon transgenesis of an established zebrafish line, Tg(Flk:Ras-cherry)^{s896} [82,83]. Embryos were co-injected (PV pneumatic pico pump) at the one-cell stage with the pminiTol2 cmlc2: GalT-bPAC (4.5 pg) linear plasmid and capped transposase RNA (6.3 pg). Embryos positive for cherry fluorescence were sorted and genotyped. Genotyping to identify bPAC and Drer_Chr1 (DNA extraction control) were performed using GoTaq Green master mix (Promega). DNA samples for genotyping were extracted (lysis buffer: 10 mM Tris pH 8 2 mM EDTA 0.2% Triton X-100 200 μg/ml Proteinase K) from adult caudal fin clipping. The primer pairs used for genotyping are: bPAC (F: 5'-gtcaaccggtacttcagcatct-3' and R: 5'-tcgtagtacttctgggcctcat-3'; 473bp), GalT (F: 5'-tgatccggcagaccctggaa-3; and R: 5'-gccctcgatctcgaactcgt-3':470bp), mApple (F: 5'-ggctccaaggtctacattaagcac-3; and R: 5'-tgtagtcctcgttgtgggac-3':424bp), Drer_ch1 (F: 5'-tatacgcggccataagtactga-3' and R: 5'-gttcatttggggctttgggtat-3'; 218bp). To determine mating pairs of GalT-bPAC fish, cAMP measurements were performed. Embryos at 72 hpf obtained from each pair were incubated with IBMX (100 μM, 30 min, 28°C). Anaesthetization by incubation of tricaine (0.04% w/v) was confirmed by a reflex test of the tail. Embryos were then exposed to 2.2 μW/cm^2 blue light to stimulate GalT-bPAC or maintained in the dark for 5 min. cAMP detection was measured by a direct cAMP ELISA assay. Mating pairs that produced embryos that robustly generated cAMP in response to blue light were subsequently used in imaging experiments.

Primary culture of cardiomyocytes

The processes for neonatal cardiomyocytes isolation are modified from previous research[84]. Briefly, hearts harvested from P1-2 neonatal CD1 pups were tear into small pieces in the ice-cold HBSS containing 20 mM HEPES. Heart pieces mixed with 225 IU/ml collagenase II were incubated on the tube rotator at 37°C for 5 min. After 10-time pipetting, the released cells in the buffer were collected by centrifuge at 500 xg for 5 min. The undigested heart tissues were digested again as describe above until the undigested tissue became white and the size do not decrease. The cells from each digestion were pooled together and resuspended in the neonatal cardiomyocyte culture media, which is DMEM (#11995065) containing 10% FBS, 10% Nu Serum IV, 10 mM HEPES, 10 mM Glutamax, Penicillin and Streptomycin and ITS. The released cells that pass through 40 μm strainer plated on the regular dish to remove the most of fibroblasts at 37°C for 2 hrs. The suspended cells were collected and plated on the mouse laminin-coated dish. For the virus transduction, lentivirus was mixed with the culture media with polybrene (8 μg/ml). The lentivirus was removed after 1-day transduction. The transduced neonatal cardiomyocytes were further treated with doxycycline for 3 days.

Adult cardiomyocytes were isolated from 2-3-month-old C57BL/6 wild-type and *Slc22a3* knockout mice using the Langedorff-free method[85]. The heparin solution was intraperitoneally injected into mouse (5 U/g). After 10 min, urethane, dissolved in 0.9% NaCl, was also intraperitoneally injected into mouse (2 mg/g). When the mouse was fully euthanized, the mouse heart was exposed, and the inferior vena cava was cut to release the blood. After the injection of EDTA buffer (130 mM NaCl, 5 mM KCl, 0.5 mM NaH_2PO_4-H_2O, 10 mM HEPES, 10 mM Glucose, 10 mM BDM, 10 mM Taurine, in ultrapure H_2O) into the right ventricle, the aorta was clamped. The clamped heart was moved to the EDTA buffer containing dish and then the EDTA buffer was injected into the left ventricle. Then, the clamped heart was moved to the perfusion buffer (130 mM NaCl, 5 mM KCl, 0.5 mM NaH_2PO_4-H_2O, 10 mM HEPES, 10 mM Glucose, 10 mM BDM, 10 mM Taurine, 1 mM $MgCl_2$-$6H_2O$, in ultrapure H_2O) containing dish and the perfusion buffer was injected into left ventricle. The clamped heart was further moved to the digestion buffer (perfusion buffer with 0.5 mg/ml Collagenase II and 0.05 mg/ml protease XIV) containing dish and then the digestion buffer was injected in to left ventricle. After digestion, the heart was tear into small pieces and gently triturated to dissociate the cardiomyocytes. The digestion processes were stopped by adding stop buffer (perfusion buffer with 5% FBS) and the suspended cardiomyocytes were pass through the 70 μm strainer. The cardiomyocytes were enriched by gravity sedimentation and reintroduced calcium gradually. The cardiomyocytes were resuspended by plating media (M199 media with 5% FBS, 10 mM BDM, Penicillin and Streptomycin) and plated on the mouse laminin-coated wells at 37°C for 1 hours. After washing out the unattached cells by culture media (M199 media with 0.1% BSA, 10 mM BDM, Penicillin and Streptomycin, and ITS), the cardiomyocytes were cultured in culture media for further use.

Blue light stimulation for activating bPAC protein in cardiomyocytes

After 1-day transduction, neonatal cardiomyocytes were treated with 100 ng/ml doxycycline for three days and then treated with 100 μM Trolox for 4 hours. bPAC-expressing neonatal cardiomyocytes were put under the blue LED board in the incubator. After 3 min exposure of blue light, the neonatal cardiomyocytes were washed by ice-cold PBS once and lysed. To measure the blue light intensity, we used a Digital Handheld Optical Power and Energy Meter Console (#PM100D, Thorlabs) with a Slim Photodiode Power Sensor probe (S130C, Thorlabs). The light intensities were calculated from the power measured (W) and the probe detection surface of 0.7855cm2.

Immunocytochemistry

For the staining of Golgi-bPAC and PM-dnPKA in the neonatal cardiomyocytes or HeLa cells, cells were washed with PBS once and fixed with 3.7% formaldehyde in PEM buffer (80 mM K-PIPES pH 6.8, 1 mM $MgCl_2$, and 1 mM EGTA) for 20 minutes at room temperature. For the staining of p-RyR2 Ser2808, p-TnI Ser23/24, pPLB Ser16/Thr17, PLB, and β1AR, cells were pre-permeabilized with 0.05% saponin diluted in PEM buffer on ice for 5 minutes before fixation. Fixation was performed using 3% paraformaldehyde diluted in PBS for 10 minutes at room temperature further quenched by 50 mM NH_4Cl diluted in PBS for 10 minutes. Fixed cells were incubated with the primary antibody at room temperature for 1 hour or at 4°C for O/N in TBS containing 0.1% Triton. After the incubation with the secondary antibody at room temperature for 30 minutes, cells were mounted using antifade mounting medium with DAPI (Vector Laboratories). The images were taken by Nikon spinning disk confocal microscope.

Lysate preparation, SDS-PAGE, and Western blot analysis

After the treatments, the cardiomyocytes from neonatal and adult mice were collected and lysed by RIPA buffer containing inhibitors of proteases and phosphatases at 4°C for 30 min on the tube rotator. Supernatants were collected after centrifuging at 4°C for 10 min and the protein amounts were determined by BCA assay (Sigma). The proteins were denatured by boiling for 10 min in the DTT containing sample buffer and separated by 4-20% Mini-PROTEIN TGX gels (BIO-RAD) and then transferred to the 0.2 μm PVDF membrane (BIO-RAD). The PVDF membrane was further blocking by TBST (TBS buffer with 0.1% Tween-20) containing 3% milk at RT for 1 h and then incubated with the primary antibody in TBST containing 5% BSA at 4°C for O/N. The PVDF membrane was washed by TBST three times and then incubated with secondary antibody diluted in TBST containing 3% milk at RT for 1 hr. The unbonded secondary antibodies was removed by three times washing using TBST. The protein signals were visualized by ECL substrate (Thermo Fisher Scientific).

Zebrafish imaging and analysis

Dechorionated embryos at 72 hpf were pretreated with a DMSO control (0.1% v/v) or IBMX (100 μM, 90 min) and were anaesthetized with tricaine (0.04% w/v). Embryos were then mounted onto glass bottom imaging dishes (35 mm, MatTek) with low melting agarose (1% w/v) and maintained in tricaine for the duration of the experiment. All image series were acquired at 61 fps for 500 frames (λ_{ex}= 561 nm, λ_{em}=X nm) with a Plan Apo

40X air objective (Nikon) on a spinning disk confocal (Nikon Eclipse Ti). Baseline images were obtained and GalT-bPAC was stimulated by exposing embryos to 4.2mW/cm2 of blue light for timepoints up to 5 min. The data were analyzed using FIJI v1.53f by measuring the fluorescence intensity of a ventricular ROI and determining the time between peak systole and peak diastole. Graphs were generated using Graphpad Prism v9.3.1. All data are expressed as Δ time relative to the baseline, as a mean ± S.E.M.

Mouse cardiac pressure-volume loop acquisition and analysis

In order to assess ventricular systolic and diastolic function, we conducted pressure-volume loop experiments using a conductance catheter (Millar Instruments, Houston, TX) in mice as described in a previous study [86]. Briefly, pressure and conductance calibrations were performed. Mice were initially anesthetized by inhalation of isoflurane (1.5% mixed with 100% oxygen). An endotracheal tube was placed and connected to the ventilator, and ventilator settings were based on animal weight [87]. Mice were placed on a heating pad and body temperatures were maintained at 37ºC. Subsequently, analgesia was administered by subcutaneously injection of buprenorphine (0.05 mg/kg). Proper anesthetization was confirmed by a reflex test of the tail. 1 mg/kg Pancuronium (Sigma Life Science) was injected intraperitoneally to prevent respiratory artifacts during recordings [88]. The aortic arch and inferior vena cava were exposed with a 6-0 silk ligature placed underneath separately. The right jugular vein was cannulated for subsequent fluid and medication infusion. A thoracotomy was performed, and the pericardium was bluntly dissected to expose the left ventricular apex. A 25-gauge needle was used to make a stab incision of the apex, followed by the insertion of a 1.4-F pressure-conductance catheter (PVR-1035, Millar) through the incision. The intra-ventricular catheter position was optimized until rectangular-shaped loops were obtained (LabChart 8.5 Pro). Then, 200 μL 0.9% saline was perfused slowly to replace body fluid loss. After steady state conditions were reached in 10 minutes, Baseline PV loops were recorded with three cycles of inferior vena cava and transverse aorta occlusion in sequence. Then epinephrine (10 μg/kg) or dobutamine (18.4 μg/kg) were injected and the above steps were repeated. To estimate G_p, 10 μL hypertonic saline (15% NaCl) were rapidly injected at the end of experiment. After 5 minutes, the blood was collected from the right ventricle for a cuvette calibration to transform conductance to volume. Cardiac parameters were obtained by offline data analysis on LabChart software (8.5).

cAMP determination

Two modes of cAMP determination were performed. A direct cAMP ELISA kit (Enzo) was used in endpoint experiments and the pGloSensor (-20F) luminescence assay (Promega) was used for kinetic cAMP measurements. For time dependent cAMP production assays in HEK293 cells, Cells were transiently transfected with GalT-bPAC and the pGloSensor-20F plasmid. 24h after transfection, cells were incubated with Glosensor cAMP reagent for 1 h at 37ºC. For GalT experiments, cells were exposed to 2.2mW/cm^2 blue light for up to 300s. Luminescence measurements were acquired at 2 min intervals. Three baseline measurements were acquired after which cells were stimulated and measured for at least 20 min. Where specified cells were treated with, the PDE inhibitor IBMX (100 μM), and

positive control, forskolin (10 μM). For primary cell and zebrafish cAMP determination ELISA assays were performed to determine cAMP. To measure epinephrine-induced cAMP production in mouse neonatal cardiomyocytes, cells were treated with a range of epinephrine (2 min, 37°C). Cells were immediately lysed in 175 μL of 0.1M HCL lysis buffer for the direct cAMP determination by ELISA which was performed as directed in the kit.

Statistics

All cardiac parameters from PV looping analysis are presented as means ± S.D. and SigmaStat 3.5 was used for comparison. A paired t test was used to compare data in same group before and after chemical infusion, while other data between groups were compared with one-way ANOVA. The significant difference between groups in dnPKA-related experiments were determined using two-way ANOVA. A post hoc Student-Newman-Keuls test was further conducted to compare difference between two groups. A P value<0.05 was considered significantly.

Data availability

All data generated and analyzed are included as source data files for all main figures and figure Supplements.

Acknowledgments

We thank members of the Irannejad lab and D. Larsen for assistance, advice and valuable discussion. These studies were supported by the National Institute on General Medicine (GM133521) to R.I.

Competing financial interests

The authors declare no competing financial interests.

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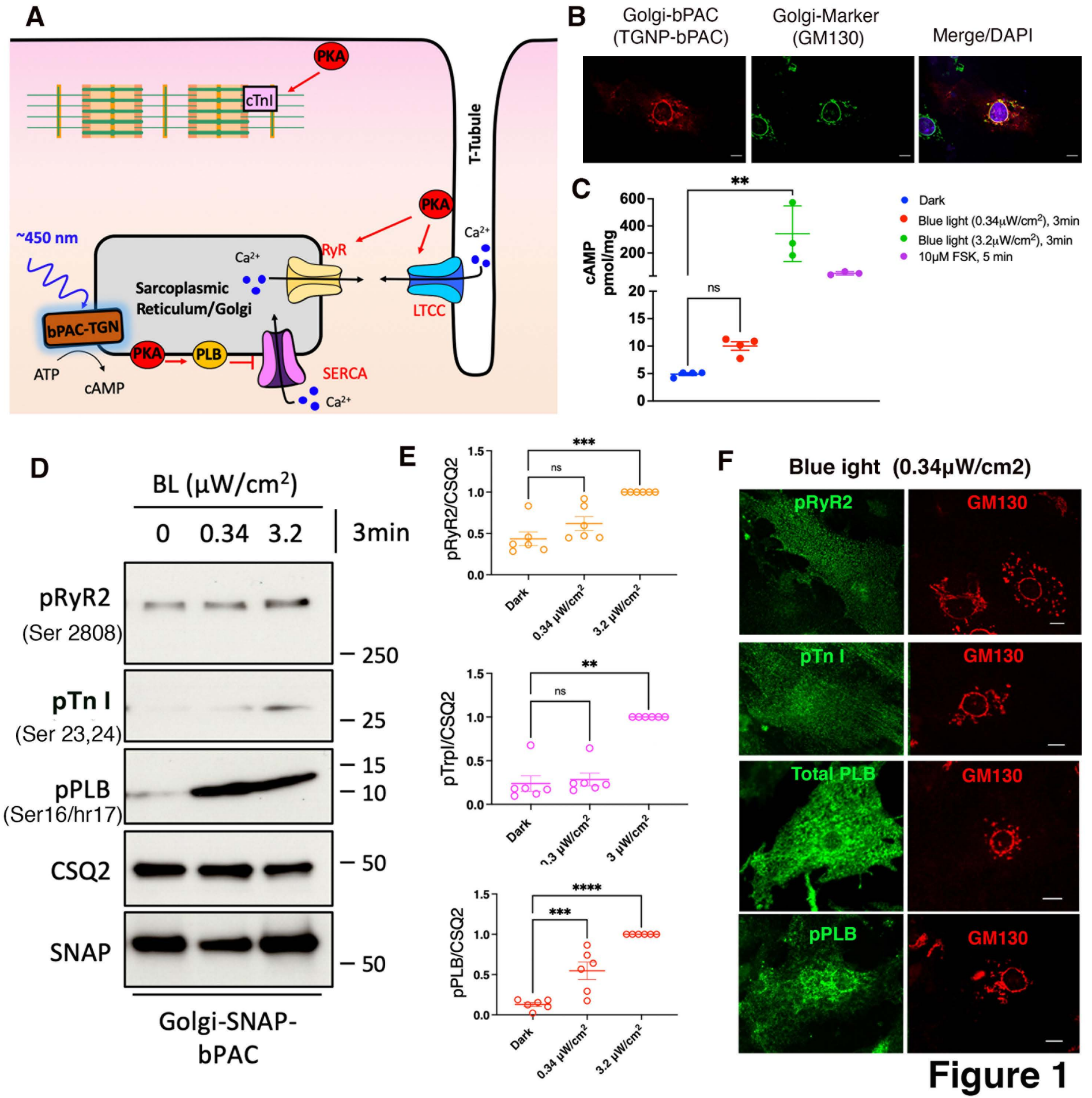
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PKA
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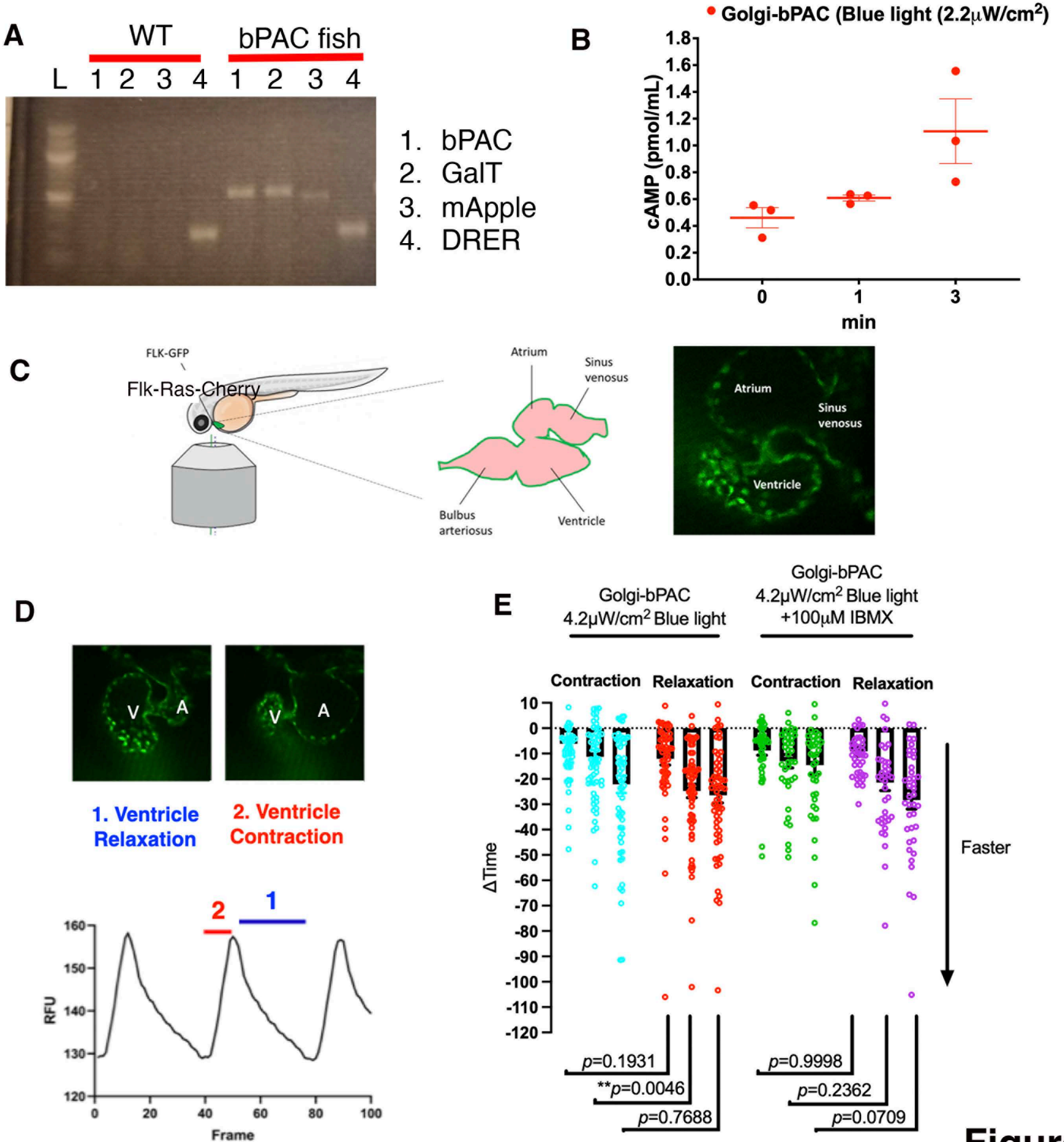
PKA
~450 nm
Ca2+
RyR
Ca2+
Sarcoplasmic
Reticulum/Golgi
LTCC
bPAC-TGN
PKA
PLB
ATP
cAMP
SERCA
Ca2+
B
Golgi-bPAC
(TGNP-bPAC)
Golgi-Marker
(GM130)
Merge/DAPI
C
cAMP
pmol/mg
600
400
200
20
15
10
5
0
**
ns
Dark
Blue light (0.34μW/cm2), 3min
Blue light (3.2μW/cm2), 3min
10μM FSK, 5 min
D
BL (μW/cm2)
0
0.34
3.2
3min
pRyR2
(Ser 2808)
pTn I
(Ser 23,24)
pPLB
(Ser16/hr17)
CSQ2
SNAP
250
25
15
10
50
50
Golgi-SNAP-
bPAC
E
pRyR2/CSQ2
***
ns
Dark
0.34 μW/cm2
3.2 μW/cm2
pTrpI/CSQ2
**
ns
Dark
0.3 μW/cm2
3 μW/cm2
pPLB/CSQ2
****
***
Dark
0.34 μW/cm2
3.2 μW/cm2
F
Blue ight (0.34μW/cm2)
pRyR2
GM130
pTn I
GM130
Total PLB
GM130
pPLB
GM130

Figure 1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WT
bPAC fish
L 1 2 3 4 1 2 3 4
1. bPAC
2. GalT
3. mApple
4. DRER
B
Golgi-bPAC (Blue light (2.2μW/cm²)
cAMP (pmol/mL)
min
C
FLK-GFP
Flk-Ras-Cherry
Atrium
Sinus venosus
Bulbus arteriosus
Ventricle
D
V
A
1. Ventricle Relaxation
2. Ventricle Contraction
RFU
Frame
E
Golgi-bPAC 4.2μW/cm² Blue light
Golgi-bPAC 4.2μW/cm² Blue light +100μM IBMX
Contraction
Relaxation
ΔTime
Faster
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**p=0.0046
p=0.7688
p=0.9998
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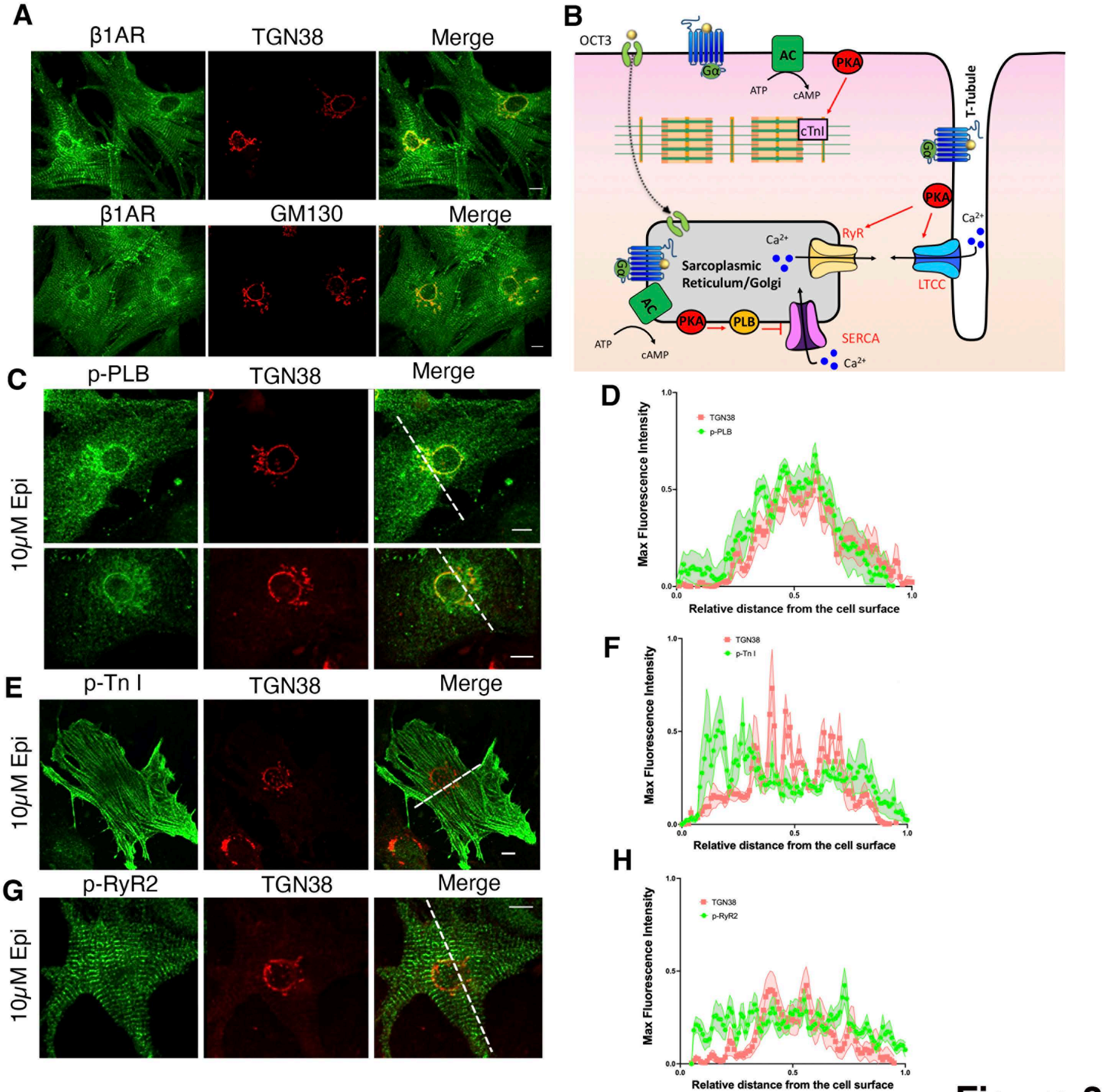
Figure 2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β1AR
TGN38
Merge
β1AR
GM130
Merge
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Gα
AC
PKA
ATP
cAMP
cTnI
T-Tubule
Gα
PKA
Ca2+
RyR
Ca2+
Sarcoplasmic
Reticulum/Golgi
Gα
LTCC
AC
PKA
PLB
SERCA
ATP
cAMP
Ca2+
C
p-PLB
TGN38
Merge
10μM Epi
D
TGN38
p-PLB
Max Fluorescence Intensity
Relative distance from the cell surface
E
p-Tn I
TGN38
Merge
10μM Epi
F
TGN38
p-Tn I
Max Fluorescence Intensity
Relative distance from the cell surface
G
p-RyR2
TGN38
Merge
10μM Epi
H
TGN38
p-RyR2
Max Fluorescence Intensity
Relative distance from the cell surface

Figure 3

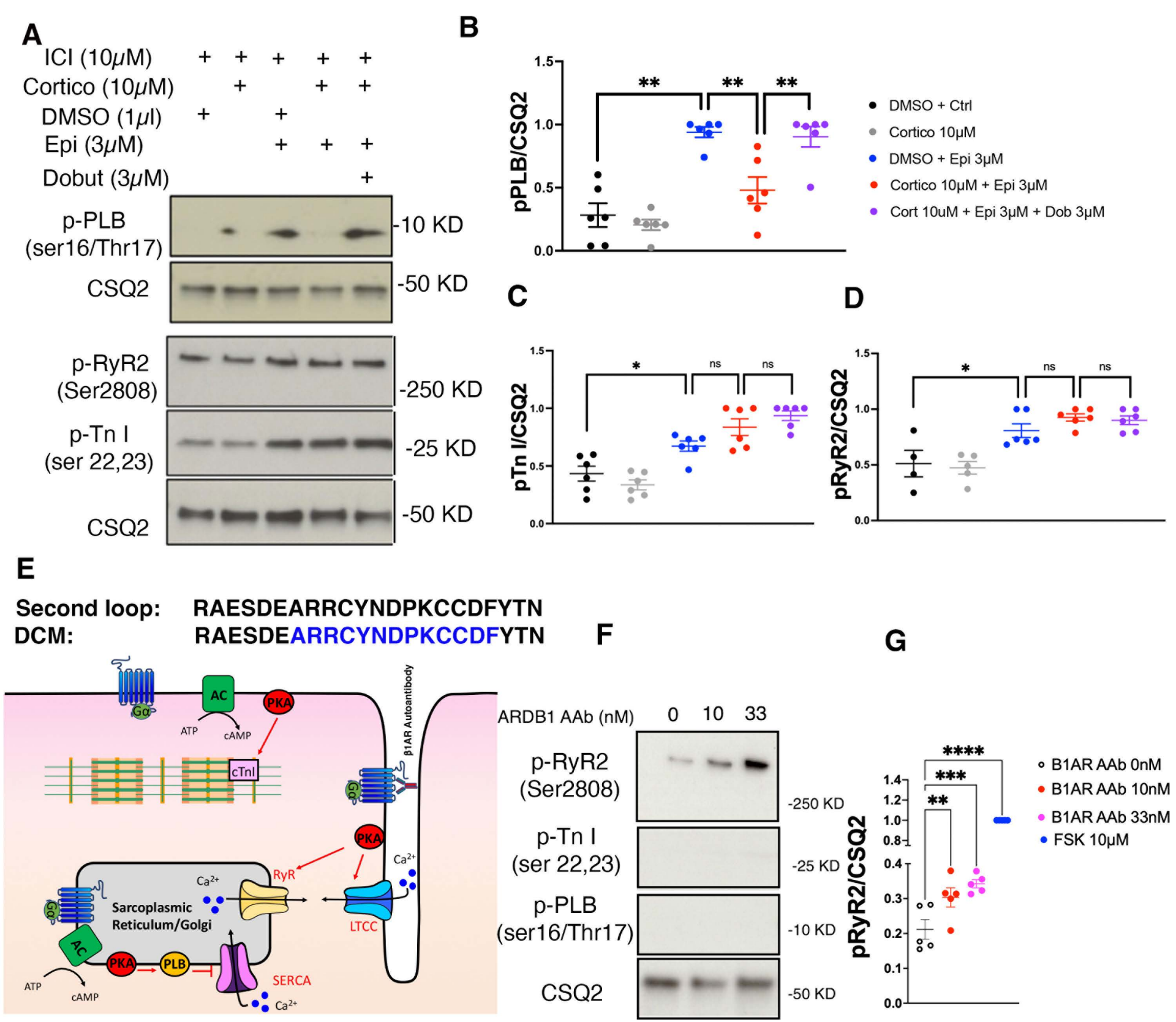
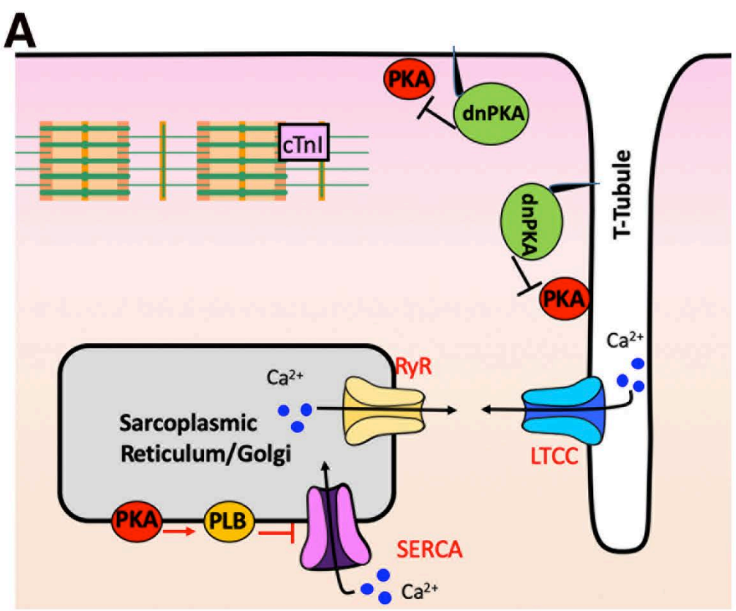

A
ICI (10μM)
Cortico (10μM)
DMSO (1μl)
Epi (3μM)
Dobut (3μM)
p-PLB (ser16/Thr17)
-10 KD
CSQ2
-50 KD
p-RyR2 (Ser2808)
-250 KD
p-Tn I (ser 22,23)
-25 KD
CSQ2
-50 KD
B
pPLB/CSQ2
DMSO + Ctrl
Cortico 10μM
DMSO + Epi 3μM
Cortico 10μM + Epi 3μM
Cort 10uM + Epi 3μM + Dob 3μM
C
pTn I/CSQ2
D
pRyR2/CSQ2
E
Second loop: RAESDEARRCYNDPKCCDFYTN
DCM: RAESDEARRCYNDPKCCDFYTN
AC
PKA
ATP
cAMP
cTnI
β1AR Autoantibody
Gα
RyR
Ca2+
Sarcoplasmic Reticulum/Golgi
LTCC
PLB
SERCA
F
ARDB1 AAb (nM)
0
10
33
p-RyR2 (Ser2808)
-250 KD
p-Tn I (ser 22,23)
-25 KD
p-PLB (ser16/Thr17)
-10 KD
CSQ2
-50 KD
G
pRyR2/CSQ2
B1AR AAb 0nM
B1AR AAb 10nM
B1AR AAb 33nM
FSK 10μM

Figure 4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PKA
dnPKA
cTnI
T-Tubule
dnPKA
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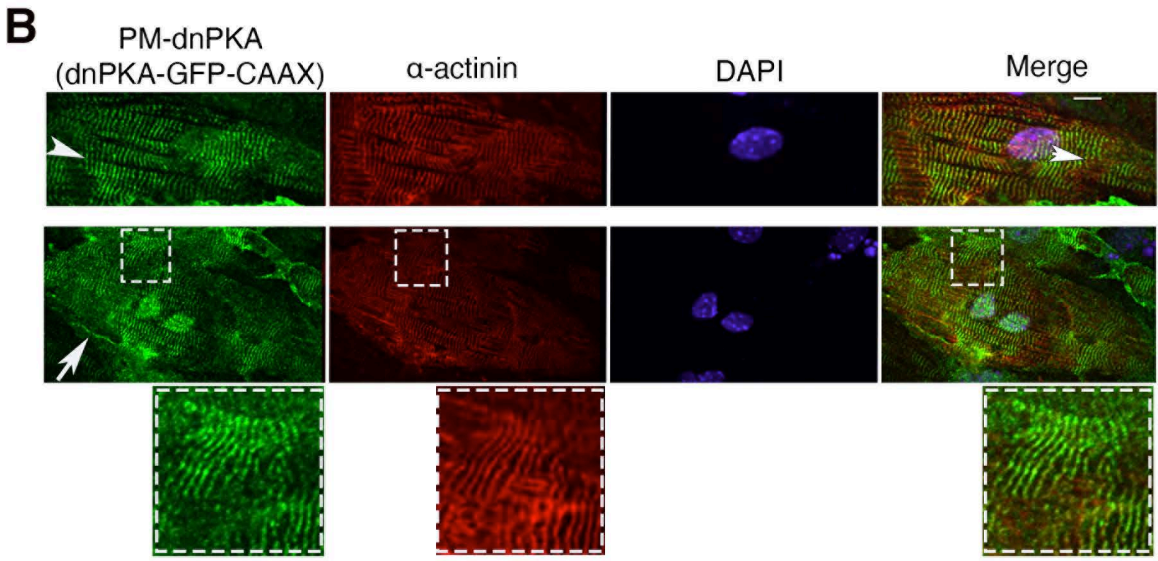
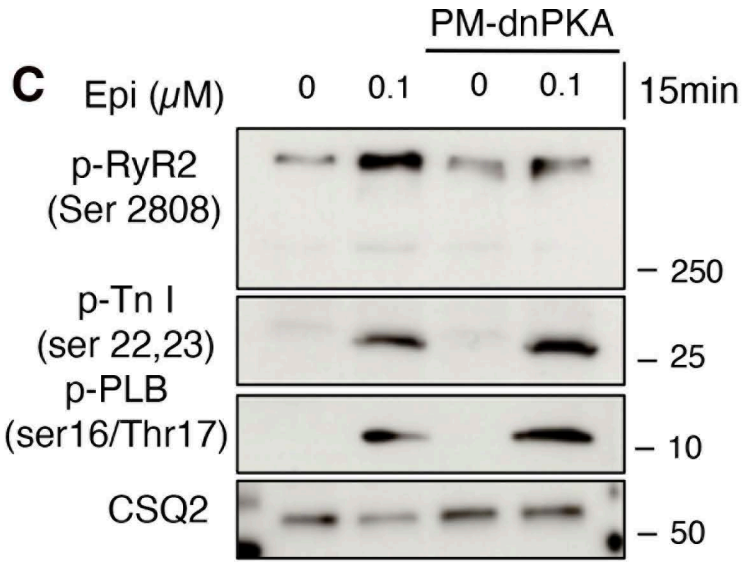
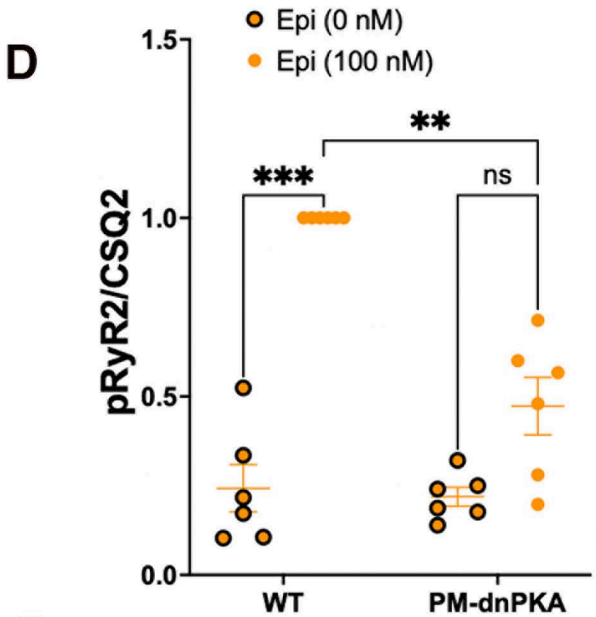
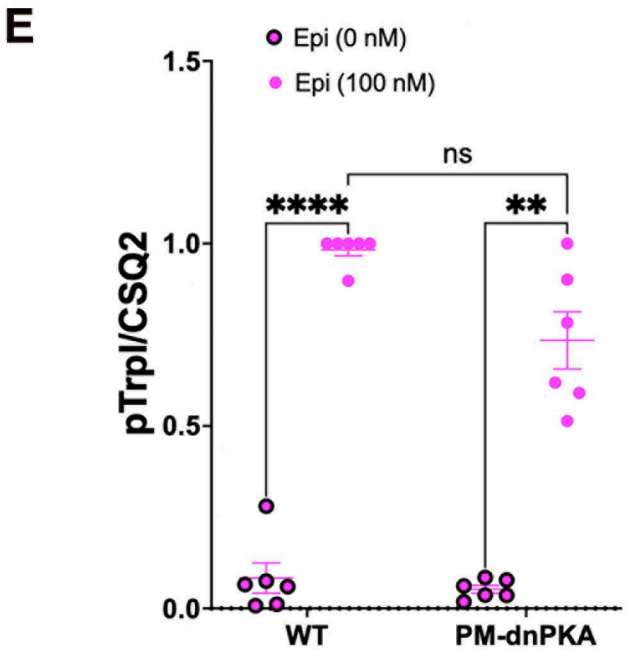
RyR
Ca2+
Sarcoplasmic
Reticulum/Golgi
LTCC
PKA
PLB
SERCA
Ca2+


B
PM-dnPKA
(dnPKA-GFP-CAAX)
α-actinin
DAPI
Merge


PM-dnPKA
C
Epi (μM)
0
0.1
0
0.1
15min
p-RyR2
(Ser 2808)
– 250
p-Tn I
(ser 22,23)
– 25
p-PLB
(ser16/Thr17)
– 10
CSQ2
– 50


D
Epi (0 nM)
Epi (100 nM)
pRyR2/CSQ2
1.5
1.0
0.5
0.0
**
***
ns
WT
PM-dnPKA


E
Epi (0 nM)
Epi (100 nM)
pTrpI/CSQ2
1.5
1.0
0.5
0.0
ns
****
**
WT
PM-dnPKA

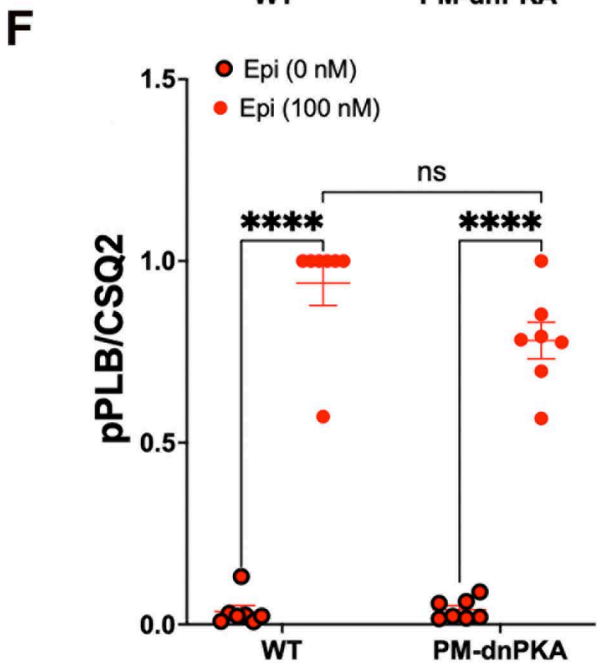

F
Epi (0 nM)
Epi (100 nM)
pPLB/CSQ2
1.5
1.0
0.5
0.0
ns
****
****
WT
PM-dnPKA

Figure 5

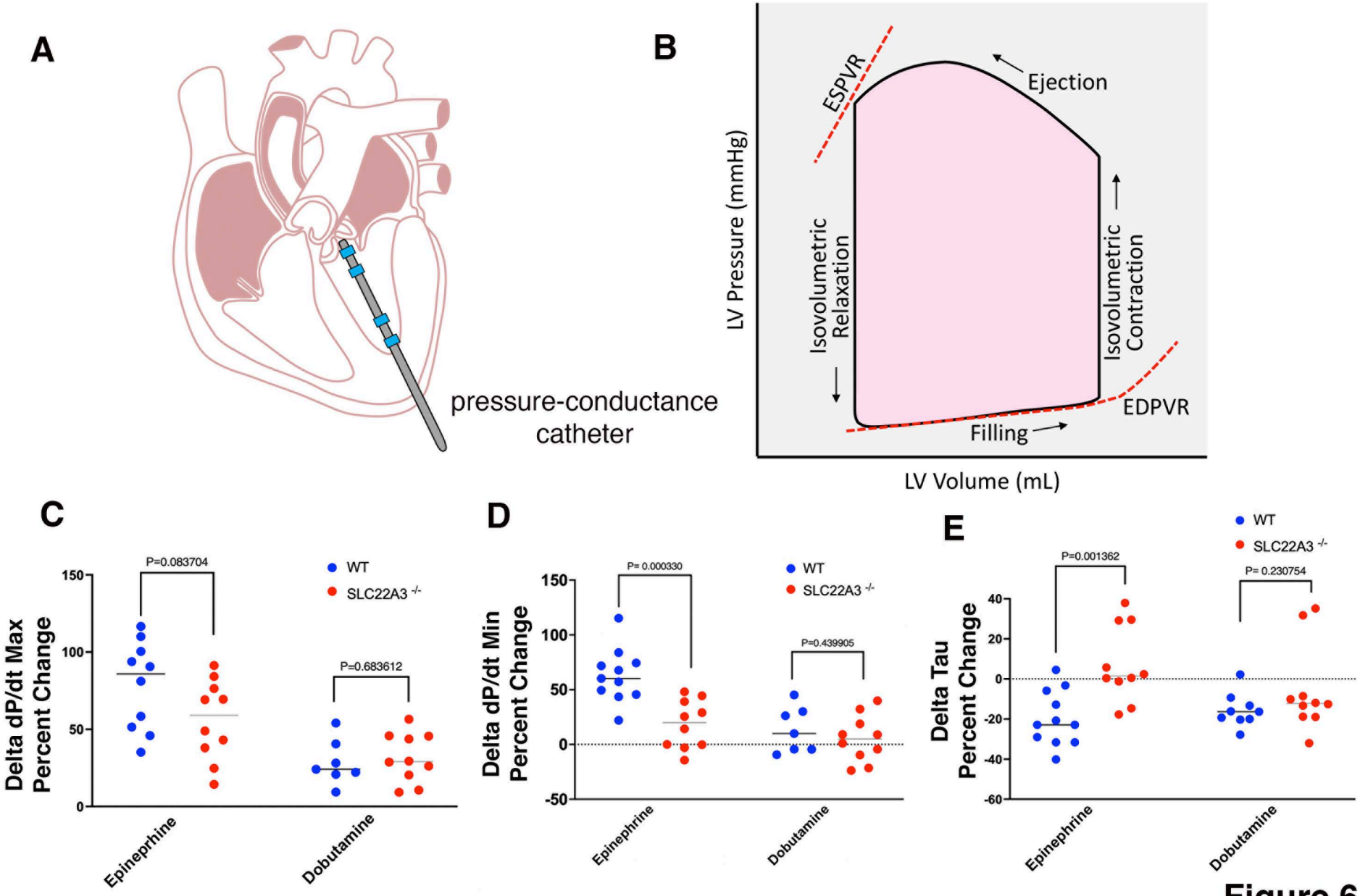

A
pressure-conductance catheter
B
ESPVR
Ejection
LV Pressure (mmHg)
Isovolumetric Relaxation
Isovolumetric Contraction
EDPVR
Filling
LV Volume (mL)
C
P=0.083704
P=0.683612
WT
SLC22A3 -/-
Delta dP/dt Max Percent Change
150
100
50
0
Epinephrine
Dobutamine
D
P= 0.000330
P=0.439905
WT
SLC22A3 -/-
Delta dP/dt Min Percent Change
150
100
50
0
-50
Epinephrine
Dobutamine
E
WT
SLC22A3 -/-
P=0.001362
P= 0.230754
Delta Tau Percent Change
40
20
0
-20
-40
-60
Epinephrine
Dobutamine

Figure 6

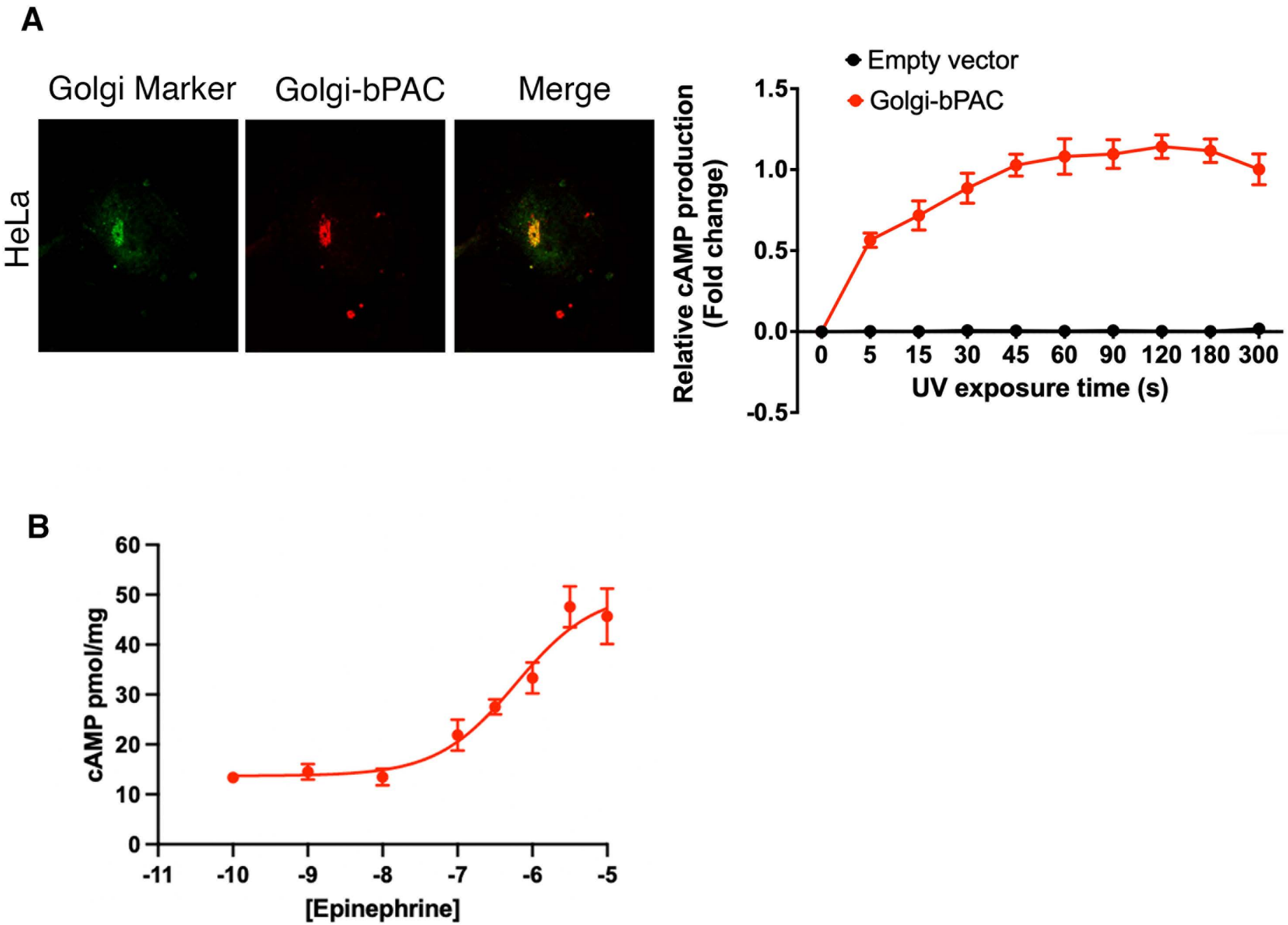

A
Golgi Marker
Golgi-bPAC
Merge
HeLa
Empty vector
Golgi-bPAC
Relative cAMP production
(Fold change)
1.5
1.0
0.5
0.0
-0.5
0
5
15
30
45
60
90
120
180
300
UV exposure time (s)
B
cAMP pmol/mg
60
50
40
30
20
10
0
-11
-10
-9
-8
-7
-6
-5
[Epinephrine]

Figure S1

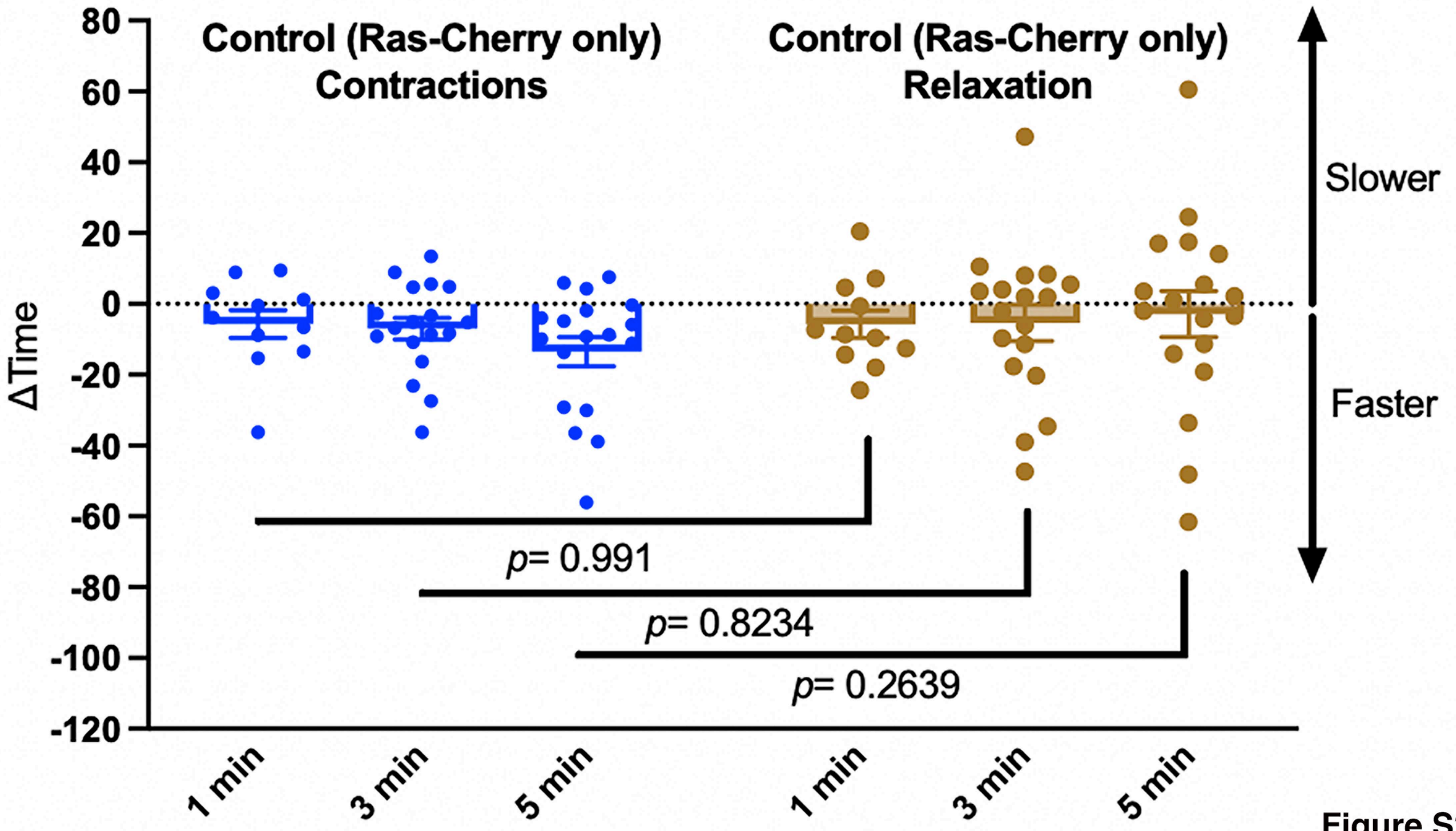

Control (Ras-Cherry only)
Contractions
Control (Ras-Cherry only)
Relaxation
ΔTime
80
60
40
20
0
-20
-40
-60
-80
-100
-120
Slower
Faster
p= 0.991
p= 0.8234
p= 0.2639
1 min
3 min
5 min
1 min
3 min
5 min

Figure S2

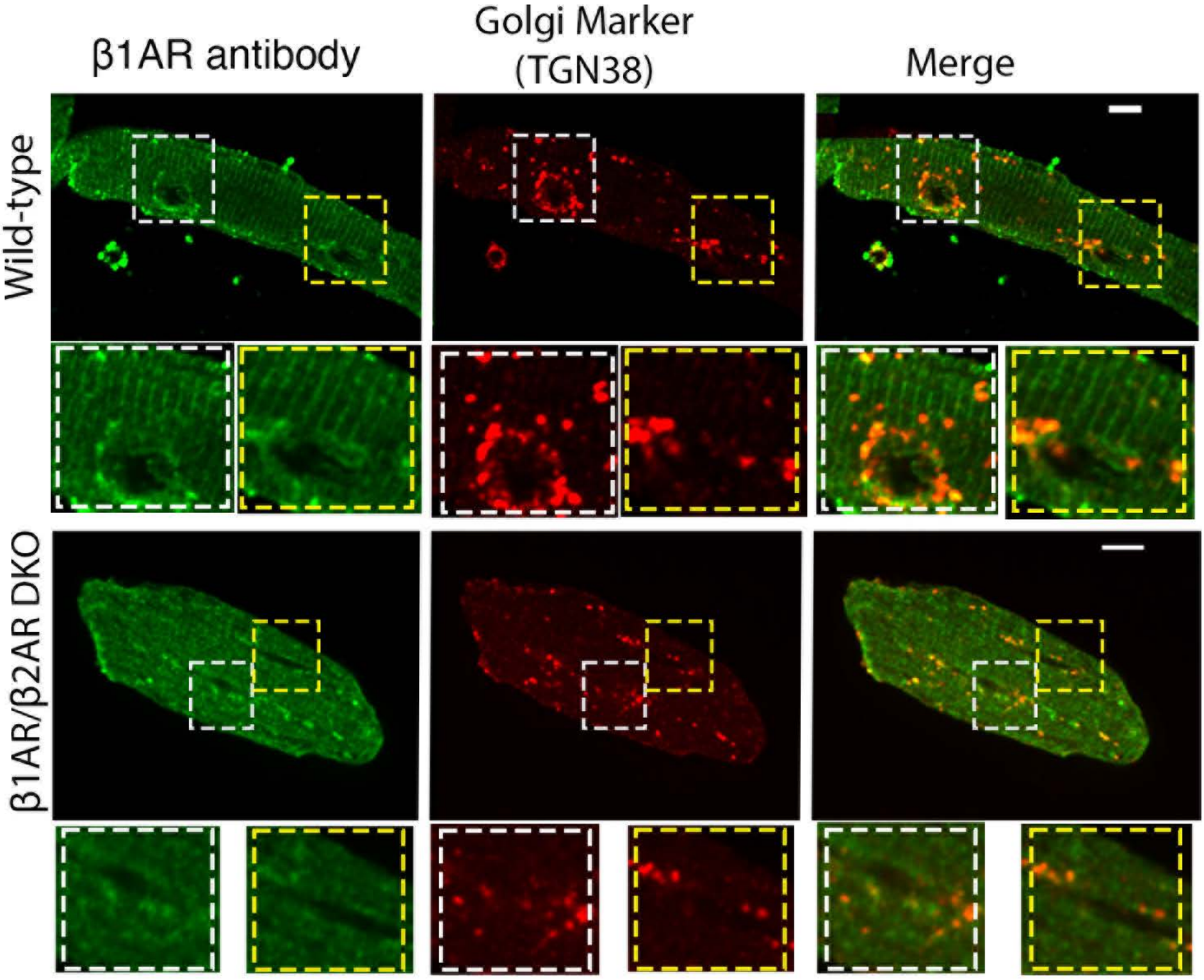

β1AR antibody
Golgi Marker
(TGN38)
Merge
Wild-type
β1AR/β2AR DKO

Figure S3

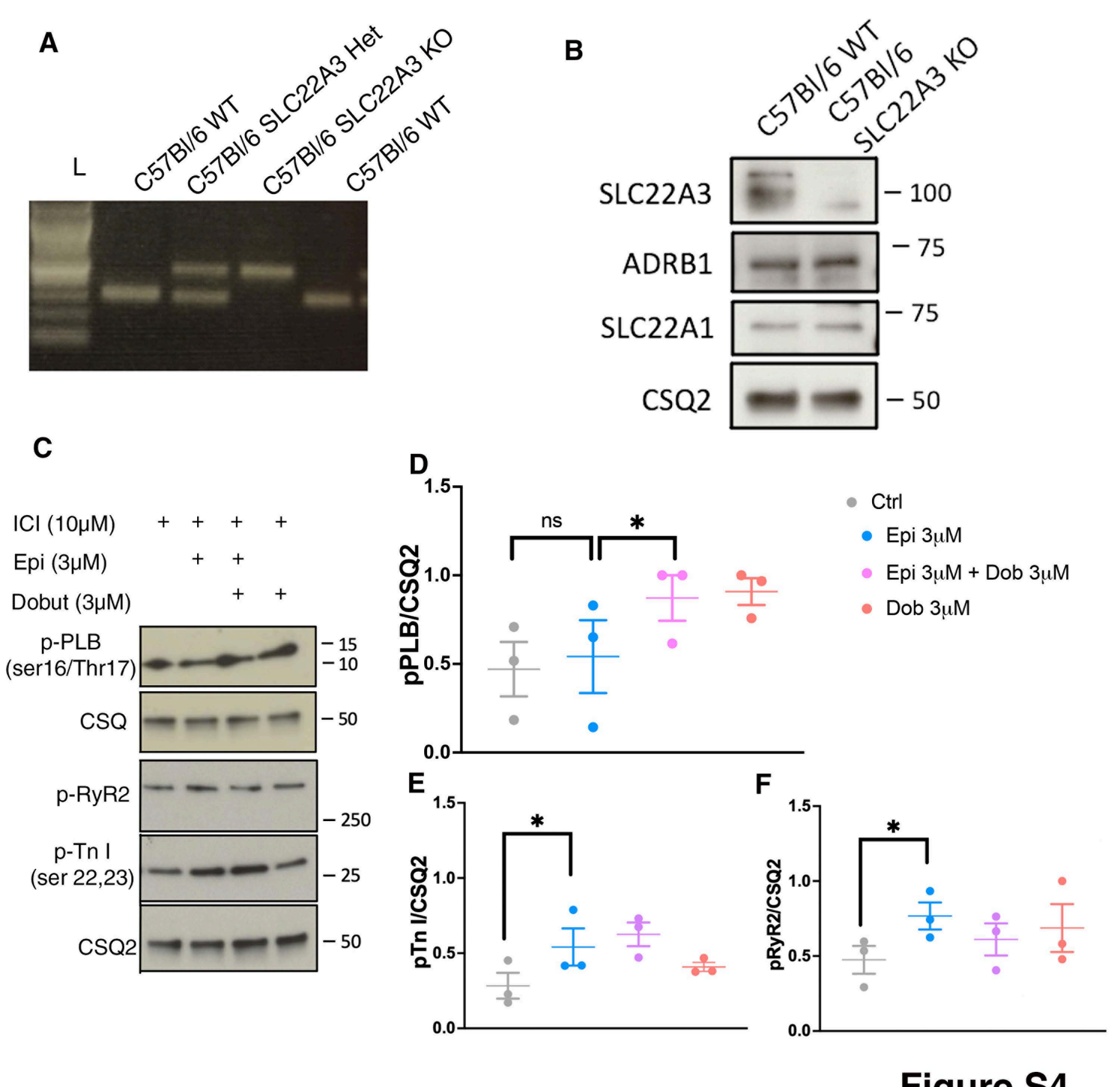

A
L
C57Bl/6 WT
C57Bl/6 SLC22A3 Het
C57Bl/6 SLC22A3 KO
C57Bl/6 WT
B
C57Bl/6 WT
C57Bl/6
SLC22A3 KO
SLC22A3
ADRB1
SLC22A1
CSQ2
100
75
75
50
C
ICI (10μM)
Epi (3μM)
Dobut (3μM)
p-PLB (ser16/Thr17)
CSQ
p-RyR2
p-Tn I (ser 22,23)
CSQ2
15
10
50
250
25
50
D
pPLB/CSQ2
ns
*
Ctrl
Epi 3μM
Epi 3μM + Dob 3μM
Dob 3μM
E
pTn I/CSQ2
*
F
pRyR2/CSQ2
*

Figure S4