Hormone-induced calcium oscillations depend on cross-coupling with inositol 1,4,5-trisphosphate oscillations.

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Hormone-Induced Calcium Oscillations Depend on Cross-Coupling with Inositol 1,4,5-Trisphosphate Oscillations

Graphical Abstract

Highlights

Ca\textsuperscript{2+} oscillation mechanisms can be distinguished using an IP\textsubscript{3} buffer

IP\textsubscript{3} buffer suppresses IP\textsubscript{3} oscillations without decreasing peak levels of IP\textsubscript{3} or Ca\textsuperscript{2+}

IP\textsubscript{3} buffering slows Ca\textsuperscript{2+} oscillation kinetics and reduces Ca\textsuperscript{2+} wave-propagation rates

Ca\textsuperscript{2+} oscillations in hepatocytes are driven by Ca\textsuperscript{2+} feedback on IP\textsubscript{3} formation

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In Brief

Gaspers et al. use a genetically encoded IP\textsubscript{3} buffer to suppress IP\textsubscript{3} dynamics during hormonal stimulation. Using this approach, they find that positive feedback of Ca\textsuperscript{2+} on IP\textsubscript{3} formation is an essential component, generating long-period, baseline-separated Ca\textsuperscript{2+} oscillations and intracellular Ca\textsuperscript{2+} waves.
Hormone-Induced Calcium Oscillations Depend on Cross-Coupling with Inositol 1,4,5-Trisphosphate Oscillations

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SUMMARY

Receptor-mediated oscillations in cytosolic Ca2+ concentration ([Ca2+]i) could originate either directly from an autonomous Ca2+ feedback oscillator at the inositol 1,4,5-trisphosphate (IP3) receptor or as a secondary consequence of IP3 oscillations driven by Ca2+ feedback on IP3 metabolism. It is challenging to discriminate these alternatives, because IP3 fluctuations could drive Ca2+ oscillations or could just be a secondary response to the [Ca2+]i spikes. To investigate this problem, we constructed a recombinant IP3 buffer using type-I IP3 receptor ligand-binding domain fused to GFP (GFP-LBD), which buffers IP3 in the physiological range. This IP3 buffer slows hormone-induced [IP3] dynamics without changing steady-state [IP3]. GFP-LBD perturbed [Ca2+]i oscillations in a dose-dependent manner: it decreased both the rate of [Ca2+]i rise and the speed of Ca2+ wave propagation and, at high levels, abolished [Ca2+]i oscillations completely. These data, together with computational modeling, demonstrate that IP3 dynamics play a fundamental role in generating [Ca2+]i oscillations and waves.

INTRODUCTION

Oscillatory Ca2+ signaling is a fundamental control process utilized by hormones and other agonists linked to the second messenger inositol 1,4,5-trisphosphate (IP3). Stimulus strength is typically encoded by increasing the frequency of cytosolic Ca2+ ([Ca2+]i) oscillations. For example, in hepatocytes, baseline-separated [Ca2+]i oscillations with an extended frequency range (seconds to many minutes) provide fine control of metabolic output over log-order hormone dose ranges (Bartlett et al., 2014; Hajnóczky et al., 1995; Rooney et al., 1989; Woods et al., 1986). Despite their critical importance, the mechanisms underlying IP3-dependent [Ca2+]i oscillations have not been fully elucidated (Berridge, 1993; Dupont et al., 2011; Meyer and Stryer, 1988; Thomas et al., 1996; Thurley and Falcke, 2011). There are two distinct classes of apparently opposing hypotheses that are very difficult to distinguish experimentally: Ca2+ excitability models in which Ca2+ oscillations occur independent of IP3 oscillations and cross-coupling models whereby IP3 oscillations are required to drive periodic Ca2+ release and reuptake.

In Ca2+ excitability hypotheses, feedback regulation by Ca2+ release from the ER gives rise to oscillations in [Ca2+]i, with IP3 serving as an upstream trigger that does not need to oscillate itself (i.e., [Ca2+]i; oscillations can occur at constant [IP3]). The complex regulatory properties of the IP3 receptor Ca2+ release channel (IP3R) provided a specific mechanism for Ca2+ excitability of the ER (De Young and Keizer, 1992; Hajnóczky and Thomas, 1997). Feedback activation through [Ca2+]i can cause the coordinated opening of IP3Rs and regenerative Ca2+ release from the ER via a Ca2+-induced Ca2+ release (CICR) mechanism, whereas delayed negative feedback by Ca2+ can result in the subsequent closing of IP3Rs and the return of [Ca2+]i baseline through the action of Ca2+-pumps (Dupont and Goldbeter, 1993; Thomas et al., 1996; Wakui et al., 1989). Thus, the sequential Ca2+-dependent activation and inactivation of IP3Rs can give rise to an autonomous oscillator that generates periodic [Ca2+]i spikes. Mathematical models based solely on IP3R kinetics yield [Ca2+]i oscillations that occur at high frequency (seconds) and within a limited range of [IP3] or phospholipase-C (PLC) activity (De Young and Keizer, 1992). Experimental evidence supports the existence of such a fast [Ca2+]i oscillator mechanism in some cell types, activated by a static increase in average [IP3] (Keizer et al., 1995; Lechleiter and Clapham, 1992; Sneyd et al., 2006).

In many other cell types, however, [Ca2+]i signals evoked with physiologically relevant agonist doses have much lower frequencies (of the order of minutes) than the oscillations observed on periodic IP3 opening (Bartlett et al., 2014; Haroutunian et al., 1991; Osipchuk et al., 1990; Politi et al., 2006; Rooney et al., 1989; Woods et al., 1986). In hepatocytes, the slow [Ca2+]i oscillations observed in hormone-stimulated intact cells
Ca^{2+} release can occur by negative feedback processes such as Ca^{2+} inactivation of IP_{3}R, elimination of IP_{3} by Ca^{2+}-activation of inositol 1,4,5-trisphosphate 3-kinase (ITPK), or inhibition of receptor-stimulated PLC by protein kinase C (PKC). Thus, Ca^{2+}-dependent feedback on either PLC, ITPK, or PKC, alone or in combination, has the potential to generate oscillations in [IP_{3}] and drive [Ca^{2+}] spiking (Politi et al., 2006).

Consistent with cross-coupling models, [Ca^{2+}] spiking has been shown to be accompanied by synchronous fluctuations in IP_{3} or phosphatidylinositol 4,5-bisphosphate levels in intact cells (Haroutunian et al., 1991; Hirose et al., 1999; Matsu-ura et al., 2006; Várnai and Balla, 1998). This may be an indication that IP_{3}-Ca^{2+} cross-coupling is involved in the regulation of [Ca^{2+}] oscillations. However, an alternative interpretation would be that the IP_{3} fluctuations are an epiphenomenon mediated by Ca^{2+}-dependent changes in IP_{3} metabolism and are nonessential for generating [Ca^{2+}] oscillations (Dupont et al., 2003; Tanimura et al., 2009). We have taken a different approach from trying to measure IP_{3} oscillations and correlate [IP_{3}] changes with [Ca^{2+}] oscillations, focusing instead on modifying IP_{3} dynamics with a genetically encoded IP_{3} buffer designed to function within the physiological range of [IP_{3}]. The recombinant cytosolic IP_{3} buffer was constructed by the in-frame fusion of the N-terminal 620 amino acids of the type-I IP_{3}R to the C terminus of green or red fluorescent protein (GFP-LBD or DsRed-LBD). Previous studies have shown that the N terminus of the IP_{3}R expressed in E. coli can bind to IP_{3} with similar affinity to native IP_{3}R (Yoshikawa et al., 1996).

Chemical Ca^{2+} buffers and recombinantly expressed Ca^{2+}-binding proteins have been successfully employed to investigate the role of Ca^{2+} dynamics in numerous processes. IP_{3}-binding proteins should prove equally useful to probe the role of IP_{3} dynamics in generating Ca^{2+} spikes. The expression of GFP-LBD is expected to slow the kinetics of agonist-evoked IP_{3} turnover without modifying the free steady-state [IP_{3}]. Moreover, our modeling studies demonstrate that an IP_{3} buffer allows us to go beyond determining the causality between [IP_{3}] and [Ca^{2+}] oscillations; it is also an ideal experimental tool to distinguish between positive versus negative-feedback effects of Ca^{2+} on IP_{3} metabolism in controlling the generation of oscillatory Ca^{2+} signals (Politi et al., 2006).

The data presented here show that GFP-LBD can bind IP_{3} and decrease the rate of IP_{3} rise during agonist stimulation, which disrupts [Ca^{2+}] spikes in COS cells and primary hepatocytes. This perturbation of Ca^{2+} signaling was due to the ability of GFP-LBD to bind IP_{3}, because a mutant that does not bind IP_{3} had no effect on agonist-induced [Ca^{2+}] responses. Increasing the level of GFP-LBD expression correlated with a loss of repetitive Ca^{2+} spiking and the appearance of distorted [Ca^{2+}] responses with slower kinetics and smaller amplitudes. These data suggest that [IP_{3}] increased to a level sufficient to activate the IP_{3}R but lacked a self-amplifying mechanism required for robust spikes of Ca^{2+} release and propagation of intracellular [Ca^{2+}] waves. Finally, introducing an IP_{3} buffer into a mathematical model based on the positive feedback of Ca^{2+} on PLC reproduced the experimental data. Taken together, these findings provide strong evidence that dynamic fluctuations of IP_{3} are an essential component in the generation of [Ca^{2+}] spikes and propagation of intracellular Ca^{2+} waves.

RESULTS

Expression of GFP-LBD in COS Cells

The properties of GFP-LBD were determined in COS cells transiently transfected with either GFP alone, GFP-LBD, or a nonbinding mutant of GFP-LBD, with a single amino acid substitution in the IP_{3}-binding site (GFP-R265QLBD; Yoshikawa et al., 1996). Western blot analysis of cells transfected with GFP-LBD or GFP-R265QLBD revealed a band at ~100 kDa, which corresponds to the full-length fusion protein (Figure S1A). Confocal images of COS cells expressing GFP-LBD or GFP-R265QLBD revealed a cytosolic distribution, similar to that observed with GFP (Figure S1B). Permeabilization of the plasma membrane with digitonin resulted in rapid loss of the GFP fusion proteins, suggesting they are not bound to cytoskeletal elements or organelles.

Although GFP-LBD appeared to be freely diffusible, it could potentially interact with endogenous proteins, including plasma membrane and intracellular ion channels, and thereby modify agonist-induced Ca^{2+} influx and/or ER Ca^{2+} content. To test these possibilities, COS cells expressing GFP, GFP-LBD, or GFP-R265QLBD were incubated in Ca^{2+}-free medium and the ER Ca^{2+} stores were released by treatment with 50 μM cyclopiazonic acid (CPA), followed by addition of 1.5 mM CaCl_{2} to measure store-operated Ca^{2+} influx (Figures S1C–S1E). GFP-LBD did not affect the size of the Ca^{2+} store, monitored by the rate and magnitude of CPA-induced Ca^{2+} release, and did not alter the rate or amplitude of Ca^{2+} influx elicited by subsequent Ca^{2+} add back (Figures S1C–S1E). Similar results were obtained with the purinergic agonist ATP. GFP-R265QLBD also had no effect on intracellular Ca^{2+} release or Ca^{2+} influx (Figures S1F and S1G). Finally, there was no effect of GFP-LBD on resting [Ca^{2+}]_{i}, indicating that it did not alter basal [Ca^{2+}]_{i} homeostasis in the absence or presence of extracellular Ca^{2+} (Figures S1D and S1H). Similar results were obtained in hepatocytes (Figure S2A).

Because the intracellular concentration of the IP_{3} buffer is an important parameter for our analysis, we used a standard curve constructed with recombinant GFP to estimate the cytoplasmic concentration of each fusion protein on a
cell-by-cell basis, as described previously (Politi et al., 2006). The mean levels of intracellular expression in COS cells for GFP-LBD and GFP-R265QLBD were similar (13 ± 1 μM and 12 ± 1 μM, respectively), whereas GFP alone was expressed at somewhat higher levels (22 ± 1 μM; see Table S1). As expected, there was an increase in the amount of total IP3 binding measured in lysates prepared from populations of COS cells transfected with GFP-LBD compared to GFP alone (79 ± 6 versus 20 ± 1 fmoles of IP3/mg cell protein, respectively, at 9.6 nM 3H-IP3).

These data demonstrate that the ligand-binding domain of GFP-LBD is expressed in the correct confirmation and is able to bind IP3. In addition, GFP-LBD does not modify the activity of plasma membrane Ca2+ channels, the size of internal Ca2+ stores, or the basal levels of [Ca2+]i.

**GFP-LBD Blocks Agonist-Induced [Ca2+]i Oscillations in COS Cells**

COS cells were transiently transfected with either GFP-LBD or GFP, and the [Ca2+]i responses to ATP stimulation at submaximal (1 μM) and then maximal (100 μM) doses were monitored with fura-2. Data from both expressing and nonexpressing cells were recorded simultaneously from the same microscope field. Figure 1 shows representative single-cell Ca2+ traces from coverslips transfected with either GFP (Figures 1A and 1B) or GFP-LBD (Figures 1C and 1D); in each case, the top panels show responses for untransfected cells from the same field as the transfected cell responses shown in the middle panels. Data are summarized in Figures 1E and 1F. The addition of 1 μM ATP elicited periodic, baseline-separated [Ca2+]i oscillations in >90% of the COS cells that did not express the transgene.
GFP-LBD Suppresses \([\text{Ca}^{2+}]_i\) Oscillations in Hepatocytes

Hepatocytes provide one of the most well-characterized examples of frequency-modulated \([\text{Ca}^{2+}]_i\) oscillations in primary cells and tissues, where they play a key role in the regulation of hepatic metabolism (Bartlett et al., 2014; Hajnoczky et al., 1995; Thomas et al., 1996). Figure 2 shows the effects of GFP-LBD expression on hormone-stimulated \([\text{Ca}^{2+}]_i\) signaling in primary cultures of rat hepatocytes. Figure 2A shows representative results from these experiments.
single-cell [Ca$^{2+}$]$_i$ traces from hepatocytes expressing GFP or different levels of GFP-LBD. GFP-LBD-positive cells were divided into low- and high-expressing cells using a cutoff that corresponded to a calculated intracellular GFP concentration of 10 μM. The effects of GFP or GFP-LBD on the pattern of hormone-evoked [Ca$^{2+}$]$_i$ responses are summarized in Figure 2B.

Stimulation of GFP-expressing hepatocytes with vasopressin (VP) induced repetitive [Ca$^{2+}$]$_i$ spiking that increased in frequency in a dose-dependent manner until a sustained plateau of [Ca$^{2+}$]$_i$ was achieved (Figure 2A), consistent with the frequency modulation reported in previous studies (Rooney et al., 1989; Woods et al., 1986). Submaximal VP (3 nM) evoked repetitive [Ca$^{2+}$]$_i$ spiking in 60% of the GFP-positive hepatocytes (Figure 2B) with similar kinetic properties to those observed in untransfected hepatocytes (Rooney et al., 1989). In both GFP- and GFP-LBD-expressing cells, the full scope of hormone-evoked Ca$^{2+}$ responses was observed after hormone treatment, ranging from no response through repetitive oscillations to peak and plateau maximal increases in [Ca$^{2+}$]$_i$ (Figure 2B). Importantly, in hepatocytes, baseline-separated [Ca$^{2+}$]$_i$ spikes could be elicited by VP in the presence of GFP-LBD. However, with increasing expression levels, GFP-LBD reduced the percentage of cells exhibiting repetitive baseline-separated [Ca$^{2+}$]$_i$ spikes (Figure 2B). In addition, there was a marked broadening of the individual [Ca$^{2+}$]$_i$ transients with increasing levels of the GFP-LBD IP$_3$ buffer (Figure 2). In control (GFP-expressing) hepatocytes, the widths of consecutive spikes remained constant, averaging 22 ± 1 s (n = 27 cells). The spike duration was significantly longer in GFP-LBD-positive cells divided into low- and high-expressing cells using a cutoff that corresponded to a calculated intracellular GFP concentration of 10 μM. The effects of GFP or GFP-LBD on the pattern of hormone-evoked [Ca$^{2+}$]$_i$ responses were observed after hormone treatment, ranging from no response through repetitive oscillations to peak and plateau maximal increases in [Ca$^{2+}$]$_i$ (Figure 2B). Importantly, in hepatocytes, baseline-separated [Ca$^{2+}$]$_i$ spikes could be elicited by VP in the presence of GFP-LBD. However, with increasing expression levels, GFP-LBD reduced the percentage of cells exhibiting repetitive baseline-separated [Ca$^{2+}$]$_i$ spikes (Figure 2B). In addition, there was a marked broadening of the individual [Ca$^{2+}$]$_i$ transients with increasing levels of the GFP-LBD IP$_3$ buffer (Figure 2). In control (GFP-expressing) hepatocytes, the widths of consecutive spikes remained constant, averaging 22 ± 1 s (n = 27 cells). The spike duration was significantly longer in GFP-LBD-positive cells divided into low- and high-expressing cells using a cutoff that corresponded to a calculated intracellular GFP concentration of 10 μM. The effects of GFP or GFP-LBD expression on the rates of Ca$^{2+}$ wave propagation and rates of [Ca$^{2+}$]$_i$ rise are summarized in Figures 2E and 2F. Submaximal agonist concentrations were defined as those that evoked oscillatory [Ca$^{2+}$]$_i$ responses in GFP and low-GFP-LBD-expressing cells, whereas maximal hormone doses evoked a peak and plateau [Ca$^{2+}$]$_i$ increase in all cells. In the GFP-expressing control cells, the rates of Ca$^{2+}$ wave propagation and rates of Ca$^{2+}$ rise were not significantly different between submaximal and maximal hormone concentrations (Figures 2E and 2F), consistent with our previous work showing that Ca$^{2+}$ wave rates are independent of agonist dose (Rooney et al., 1999). Increasing GFP-LBD expression from low to high levels progressively slowed the rates of Ca$^{2+}$ wave propagation and decreased rates of Ca$^{2+}$ rise elicited by submaximal hormone stimulation (Figure 2). Maximal VP overcame the actions of low levels of GFP-LBD expression on both [Ca$^{2+}$]$_i$ oscillation parameters but only partially reversed the effects of high GFP-LBD expression (Figures 2E and 2F). We also examined the effects of LBD on the kinetics of Ca$^{2+}$ waves using a recombinant Ca$^{2+}$-sensitive fluorescent protein, RGECO1 (Zhao et al., 2011). This protein-based Ca$^{2+}$ indicator is more slowly diffusible with lower buffering capacity compared to fura-2, so it should minimize alterations in Ca$^{2+}$ wave kinetics that might derive from indicator effects on Ca$^{2+}$ diffusion. Nevertheless, the expression of GFP-LBD still reduced Ca$^{2+}$ wave velocity in a stimulus-strength-dependent manner in our studies using RGECO1 (Figures S2B and S2C). Thus, similar results were obtained with fura-2 and RGEA1: LBD decreased the rate of [Ca$^{2+}$]$_i$ rise even at subcellular resolution and slowed the propagation of Ca$^{2+}$ waves. If [Ca$^{2+}$]$_i$ oscillations and waves were dependent only on Ca$^{2+}$-feedback effects on Ca$^{2+}$ release and reuptake, independent of oscillations in IP$_3$, the Ca$^{2+}$ dynamics should not be affected by the IP$_3$ buffering effect of GFP-LBD.

**Effect of LBD Expression on Ca$^{2+}$ Responses Elicited by Slow Release of Caged IP$_3$**

In order to further investigate whether the effects of IP$_3$ buffering on hormone-induced [Ca$^{2+}$]$_i$ oscillations are indicative of a causative role for IP$_3$ oscillations, we examined the response to a slow, continuous uncaging of IP$_3$. Progressive uncaging of IP$_3$ with low-intensity UV illumination in the absence of hormone resulted in a monophasic [Ca$^{2+}$]$_i$ rise after a brief delay, followed by...
a slow return to basal. Figure 3 shows representative traces from GFP- and GFP-LBD-expressing hepatocytes coexpressing RGECON1 for [Ca^{2+}] measurement. Importantly, there was no effect of LBD on the rate of rise (Figure 3C) or the peak amplitude (Figure 3D) of the [Ca^{2+}] increase elicited by uncaging IP$_3$. One interpretation of these data is that once the [IP$_3$] crosses a critical threshold, the primary driver of [Ca^{2+}] increase is CICR, yielding a Ca^{2+} transient that is essentially autonomous from the slowly rising IP$_3$ level. Despite the lack of effect of LBD on the rising phase, it significantly prolonged the [Ca^{2+}] spike width (Figure 3E), perhaps because it slows IP$_3$ degradation. Once the rise of IP$_3$ buffering, because the IP$_3$ buffer creates an additional cellular pool of sequestered IP$_3$.

To directly measure agonist-induced [Ca^{2+}], and IP$_3$ changes simultaneously by single-cell imaging, we used the recombinant IP$_3$-sensitive biosensor IRIS-1 (Matsu-ura et al., 2006) together with the chemical Ca^{2+} indicator Indo-1. More than 90% of nontransfected COS cells responded to increasing ATP concentrations with frequency-modulated [Ca^{2+}] spiking, whereas ATP induced only sporadic [Ca^{2+}] spikes in the presence of IRIS-1 (Figure S4). This presumably reflects the effect of IP$_3$ binding by IRIS-1 and is consistent with the sensitivity of COS cells to the IP$_3$ buffering effects of GFP-LBD shown in Figure 1. In order to examine the effect of the LBD buffer on IP$_3$ dynamics, a DsRed-LBD construct was used so that IRIS-1 and DsRed-LBD could be discriminated in cotransfected cells. Stimulation with maximal ATP caused a sustained increase in [Ca^{2+}] and a robust rise in the IRIS-1 emission ratio in both DsRed and DsRed-LBD-expressing cells (Figure S4C). DsRed-LBD did not alter the relative rates of IP$_3$R Ca^{2+} activation and inactivation. Instead, the data support a role for rapid dynamic modulation of IP$_3$ levels specifically during hormone-induced [Ca^{2+}] oscillations.

**Effect of GFP-LBD on Agonist-Induced IP$_3$ Increases**

The effects of GFP-LBD expression on intracellular IP$_3$ levels were measured in populations of COS cells using an IP$_3$ mass assay. Stimulation with submaximal ATP (1 μM) for 60 s increased total intracellular IP$_3$ by 30% ± 1% above basal in control GFP-expressing cells, whereas IP$_3$ accumulation in GFP-LBD-expressing cells was significantly greater at 69% ± 5% above basal (p < 0.001). No significant difference in the basal levels of IP$_3$ could be detected between the two cell populations. The higher accumulation of total IP$_3$ in the presence of GFP-LBD is an expected consequence of IP$_3$ buffering, because the IP$_3$ buffer creates a nontransfected pool of sequestered IP$_3$.

Figure 3. Effect of GFP-LBD on [Ca^{2+}] Response to Slow Uncaging of IP$_3$

(A and B) Hepatocytes cotransfected with RGECON1 and either GFP (A) or GFP-LBD (B) were loaded with caged IP$_3$ (2 μM; 1 hr). The gray area shows the duration of slow IP$_3$ uncaging elicited by low-intensity UV illumination (50 ms exposures at 2 Hz). VP was added at the arrow 5 min after stopping UV illumination.

(C-E) Summary of the effects of GFP and GFP-LBD on the rate of [Ca^{2+}] rise (C), peak amplitude (D), and spike width (E). Data are mean ± SEM (n ≥ 50 cells from four separate experiments). *Significantly different from GFP-expressing cells (p < 0.05); #significantly different from control (GFP) VP response; p < 0.05.
magnitude of [IP₃] increase induced by maximal ATP but slowed the rate of IP₃ rise by about 5-fold (Figures S4D and S4E). As with our measurements of total IP₃ formation, this is what is predicted for an IP₃ buffer and serves to validate our approach using the LBD-expression constructs to modify the kinetics of IP₃. In common with GFP-LBD, DsRed-LBD completely eliminated the occurrence of ATP-induced [Ca²⁺] oscillations in COS cells. Therefore, it was not possible to determine the effect of LBD on [IP₃] dynamics during [Ca²⁺] spiking in these cells.

We also used IRIS-1 to examine the effects of DsRed-LBD expression on IP₃ and [Ca²⁺] dynamics in hormone-stimulated hepatocytes (Figure 4). At low levels of expression, IRIS-1 did not block [Ca²⁺] oscillations induced by submaximal VP but slowed the rising phase of the [Ca²⁺] spike (compare DsRed to None in Figure 4C). This is expected because IRIS-1 is itself an IP₃ buffer, but fortunately, its buffering effect is not sufficient to prevent the [Ca²⁺] oscillations in hepatocytes. Importantly, for each [Ca²⁺] spike, there was a parallel transient increase in the IRIS-1 emission ratio, indicating that Ca²⁺ and IP₃ oscillations are synchronized in hepatocytes (Figure 4A). The onset of the [Ca²⁺] and IP₃ spikes appeared to occur simultaneously, whereas peak [Ca²⁺] was achieved while the IP₃ level was still rising (Figure 4B). The declining phase of the IP₃ oscillations clearly lagged behind the relaxation of the [Ca²⁺] spike, and this was also apparent in the longer peak duration for IP₃ (Figures 4B and 4D). These data are consistent with positive feedback of Ca²⁺ on IP₃ generation (Politi et al., 2006). Coexpression of the IP₃ buffer DsRed-LBD with IRIS-1 slowed the rate of rise of [IP₃], and this was accompanied by a slowing and broadening of the [Ca²⁺] spike (Figure 4), similar to that observed with GFP-LBD (Figures 2 and 3). Although DsRed-LBD expression slowed the rates of [IP₃] increase evoked by both submaximal and maximal hormone stimulation, it did not alter the magnitude of these IP₃ increases (Figures 4E and 4F).

The data presented above demonstrate that the IP₃ buffers DsRed-LBD and GFP-LBD act to suppress [Ca²⁺] oscillations by slowing the rate of increase in free IP₃ and not by inhibiting IP₃ formation. This is consistent with a key role for IP₃ dynamics in driving [Ca²⁺] oscillations. It should be noted that IRIS-1 also partially inhibited agonist-induced [Ca²⁺] oscillations, even though it has a lower affinity for IP₃ than the type-I IP₃R used to derive the LBD-based IP₃ buffers (Kd of 500 nM versus 40 nM, respectively; Matsu-ura et al., 2006; Yoshikawa et al., 1996). These findings indicate that IRIS-1 (and presumably other IP₃ indicators) can interfere with Ca²⁺ dynamics by buffering agonist-induced changes in IP₃.
Mathematical Modeling of IP3 Buffer Effects on IP3-Induced Ca2+ Oscillators

The data presented here provide evidence that oscillations of IP3 are essential for the generation of [Ca2+]i spiking in many cell types. Different mechanisms for feedback regulation of IP3 levels by Ca2+ ions have been proposed that can result in coupled oscillations of [IP3] and [Ca2+]i: (1) inhibition of IP3 generation through PKC-mediated inactivation of agonist receptors or PLC; (2) Ca2+-mediated activation of IP3 removal by ITPK; and (3) activation of PLC by Ca2+ (see Politi et al., 2006 and Sneyd et al., 2006). We have investigated how a molecular IP3 buffer (e.g., GFP-LBD) is predicted to affect these oscillator mechanisms by analyzing prototypical mathematical models for each mechanism. The models incorporate the regulatory properties of the IP3R (stimulation by IP3 and activation and delayed inhibition by [Ca2+]i) together with one of the above-mentioned feedback mechanisms (Figure S5).

In the absence of IP3 buffer, all models reproduce the experimentally observed encoding of agonist dose into [Ca2+]i oscillation frequency and increased the latency to first spike (Figures 5E and 5F), but the oscillations persisted even at very high concentrations of IP3 buffer (30 μM). By contrast, in the positive-feedback model with Ca2+-activated PLC, IP3 buffer (5 μM) completely abolished oscillations. Instead, stepwise increases of [Ca2+]i resemble the experimental observations in COS cells (Figure 1). In this model, plasma-membrane Ca2+ fluxes were neglected, assuming that they are small relative to the fluxes across the ER membrane. When substantial Ca2+ fluxes through the plasma-membrane Ca2+ ATPase were added to the model, the IP3 buffer converted [Ca2+]i oscillations into slow and broad responses to agonist stimulation (Figure 5H) that are similar to those observed in hepatocytes (Figure 2). For lower concentrations of IP3 buffer (~1 μM), the oscillations persisted but had lower frequencies (not shown).

In summary, negative-feedback models involving either PKC or ITPK cannot account for the experimentally observed effects of GFP-LBD. By contrast, the positive-feedback model with Ca2+-activated PLC reproduces the distinct patterns of broadened [Ca2+]i oscillations and amplitude-modulated stepwise [Ca2+]i increases observed in the presence of the IP3 buffer in hepatocytes and COS cells. This provides further evidence that IP3 dynamics are an intrinsic component of the Ca2+ oscillator, at least for these cell types.

Figure 5. Simulations of the Effect of GFP-LBD Expression in Mathematical Models of Ca2+/IP3 Oscillations

Ca2+ and IP3 oscillations were modeled as described in Supplemental Information in the absence (A–D) and presence (E–H) of LBD IP3 buffer. Parameters used are given in Table S2. Stepwise agonist dose increases occur at each arrow. All models show frequency encoding of stimulus strength in the absence of LBD. LBD does not abolish oscillations in models with PKC-mediated receptor/PLC inactivation (E) or Ca2+-dependent IP3 metabolism by ITPK (F). Ca2+ oscillations are abolished by LBD in models with Ca2+ activation of PLC (G and H). Graded plateau [Ca2+]i increases occur when the plasma membrane fluxes are neglected (G), and slow broad [Ca2+]i transients occur when Ca2+ fluxes through the PMCA are substantial (H). LBD concentrations were 30 μM in (E), (F), and (H) and 5 μM in (G).
We have used engineered IP$_3$-binding proteins expressed in intact cells to investigate the effects of slowing [IP$_3$]$_i$ dynamics on hormone-induced [Ca$^{2+}$]$_i$ oscillations. Apart from possible effects on the initial Ca$^{2+}$ spike, IP$_3$ buffers are not expected to substantially affect [Ca$^{2+}$]$_i$ oscillator mechanisms that depend only on a static increase in [IP$_3$] [e.g., CICR at the IP$_3$R]. By contrast, IP$_3$ buffering is expected to perturb the ongoing generation of repetitive [Ca$^{2+}$]$_i$ spikes that depend on rapid modulation of IP$_3$ levels to sustain the oscillatory behavior (e.g., cross-coupling between Ca$^{2+}$ and IP$_3$). Thus, IP$_3$ buffers can be used as an experimental tool to examine the causality between IP$_3$ dynamics and Ca$^{2+}$ oscillations. Moreover, computational studies have shown that an IP$_3$ buffer can be used to distinguish the type of Ca$^{2+}$-dependent feedback (positive versus negative) on IP$_3$ metabolism, because these mechanisms predict qualitatively different effects of IP$_3$ buffering (Politi et al., 2006).

Expression of molecular IP$_3$ buffers in hepatocytes and COS cells suppressed or eliminated oscillatory [Ca$^{2+}$]$_i$ signals in a concentration-dependent manner. The IP$_3$R ligand-binding domain constructs used here did not directly affect intracellular Ca$^{2+}$ release or plasma membrane Ca$^{2+}$ entry mechanisms. The effects on [Ca$^{2+}$]$_i$ oscillations were specific for GFP-LBD binding to IP$_3$ because the nonbinding mutant R265QLBD had no effect. Importantly, these IP$_3$ buffering effects were not restricted to the initial phase of the oscillations but were observed for the first [Ca$^{2+}$]$_i$ spike and all of the subsequent spikes in the oscillation train. The fact that IP$_3$ buffering affected these later Ca$^{2+}$ oscillations is a clear indication of the importance of IP$_3$ dynamics during ongoing Ca$^{2+}$ spiking.

Simultaneous direct measurement of [IP$_3$] and [Ca$^{2+}$] revealed synchronized oscillations in both messengers during hormone stimulation. Importantly, the fact that the IP$_3$ buffer slowed the rate of rise of both [Ca$^{2+}$]$_i$ and [IP$_3$] indicates that Ca$^{2+}$ dynamics are intimately tied to IP$_3$ dynamics. Moreover, the effects of GFP-LBD cannot be explained by a reduction in the steady-state or time-averaged increase in free [IP$_3$], because the peak [IP$_3$] during each [Ca$^{2+}$]$_i$ spike was unaffected and the perturbation of [Ca$^{2+}$]$_i$ and [IP$_3$] kinetics persisted throughout the train of oscillations. GFP-LBD also slowed the falling phase of each [Ca$^{2+}$]$_i$ oscillation, which is consistent with the expected interplay between Ca$^{2+}$ and IP$_3$ in the cross-coupling PLC positive feedback model (Politi et al., 2006). Thus, inactivation of the IP$_3$R by Ca$^{2+}$ negative feedback is insufficient to fully terminate Ca$^{2+}$ release until the [IP$_3$] falls, and this process is slowed by the presence of the IP$_3$ buffer.

A slow, continuous photolysis of caged IP$_3$ was used to mimic the low hormone doses that typically induce Ca$^{2+}$ oscillations in hepatocytes. Although this slow IP$_3$ uncaging could elicit a Ca$^{2+}$ spike, the rates of Ca$^{2+}$ rise were about 10-fold slower compared to those recorded after VP stimulation and also had a significantly lower amplitude. This can be explained by positive Ca$^{2+}$ feedback on PLC only occurring during hormone activation, whereas the slow uncaging of IP$_3$ in the absence of hormone does not engage this positive feedback on IP$_3$ generation. Importantly, GFP-LBD did not affect the rate of rise or amplitude of Ca$^{2+}$ increases triggered by the slow release of caged IP$_3$, whereas subsequent hormone-evoked Ca$^{2+}$ oscillations were inhibited in the same cell. These data indicate that the effects of GFP-LBD expression on hormone-induced Ca$^{2+}$ oscillations are not a simple consequence of the rate of delivery of IP$_3$ to the IP$_3$R to trigger CICR. Instead, the qualitatively different effects of IP$_3$ buffering observed with hormone compared to IP$_3$ uncaging demonstrate the importance of positive feedback to regenerate IP$_3$ during hormone stimulation and show that IP$_3$ dynamics are an essential component sustaining baseline separated Ca$^{2+}$ oscillations. Finally, our observation that hepatocytes and COS cells expressing high levels of GFP-LBD did not exhibit agonist-induced [Ca$^{2+}$]$_i$ oscillations at all but instead responded with monophasic or broad [Ca$^{2+}$]$_i$ transients indicates that [Ca$^{2+}$]$_i$ oscillations do not occur in these cells in the absence of [IP$_3$] oscillations.

Taken together, the data are consistent with a model in which [IP$_3$]$_i$ oscillations, mediated by Ca$^{2+}$-dependent feedback on IP$_3$ metabolism, are essential for repetitive, large-amplitude [Ca$^{2+}$]$_i$ spiking. Cross-coupling between Ca$^{2+}$ and IP$_3$ can occur through either positive or negative feedback mechanisms. However, our experimental and computational studies indicate that the results can only be reproduced with a positive feedback mechanism, i.e., Ca$^{2+}$-dependent activation of PLC. The IP$_3$ buffer interferes by dampening and, at high concentration, abolishing the [IP$_3$]$_i$ oscillations. Accordingly, oscillatory [Ca$^{2+}$]$_i$ spikes are slowed and prolonged at low buffer concentration and disappear at high buffer concentration.

In conclusion, this study presents evidence that Ca$^{2+}$ feedback regulation of the IP$_3$R is not sufficient itself to generate low-frequency, baseline-separated [Ca$^{2+}$]$_i$ oscillations elicited by PLC-linked hormones in hepatocytes and COS cells. Experimental manipulation of IP$_3$ dynamics with an IP$_3$ buffer has provided important insights into the mechanisms generating [Ca$^{2+}$]$_i$ oscillations and waves. Our data are consistent with a model for [Ca$^{2+}$]$_i$ spiking that combines IP$_3$-Ca$^{2+}$ cross-coupling with IP$_3$R-based Ca$^{2+}$ excitability. The combination of two coupled oscillators, one at the level of IP$_3$ generation/breakdown and the other at the level of IP$_3$R activation/inactivation, can greatly extend the frequency range for encoding hormone stimulus strength in [Ca$^{2+}$]$_i$ oscillations (Politi et al., 2006). This provides a high-fidelity signal, even at very low hormone doses, and is likely to be a widely used paradigm to fine-tune responses to stimulation.

**EXPERIMENTAL PROCEDURES**

**Cells**

COS-7 cells obtained from American Type Culture Collection were cultured in Dulbecco’s modified Eagle’s medium plus 10% fetal bovine serum. Hepatocytes were isolated by collagenase perfusion of rat livers and maintained in primary culture for 16–20 hr in Williams E medium (Hajnoczy et al., 1995; Rooney et al., 1989). Animal studies were approved by Rutgers New Jersey Medical School Institutional Animal Care and Use Committee.

**GFP-LBD Expression and IP$_3$ Binding**

Rat type 1 IP$_3$R cDNA encoding LBD, residues 1–620, and R265QLBD were ligated in frame to the C terminus of pGFP-C1 or pDsRed-C1 (Clontech Laboratories) to generate the plasmids pGFP-LBD, pDsRed-LBD, and pGFP-R265QLBD. Cells were transfected 16–48 hr prior to use. Expression of recombinant protein was confirmed by western blot analysis with anti-GFP antibody. Confocal microscopy was used to calculate the intracellular [GFP] as described previously (Politi et al., 2006). Quantitation of IP$_3$-binding...
sites in lysates of transfected COS cells was determined using \[^{3}H\]-IP₃ (Joseph et al., 1995). Agonist-induced formation of IP₃ in intact COS cells was measured using a commercial IP₃ mass assay (GE Healthcare).

### Ca²⁺ and IP₃ Imaging

Live-cell imaging was performed with cells plated on glass coverslips. Fura-2 or Indo-1 were loaded as acetoxymethyl esters for 20–40 min. RGECO1 was cotransfected with the LBD constructs as required. The cells were measured using a commercial IP₃ mass assay (GE Healthcare).

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**AUTHOR CONTRIBUTIONS**

Imaging studies were carried out by L.D.G., P.J.B., P.B., and W.M.; IP₃ uncaging by P.J.B.; and biochemical studies by J.J. and S.K.J. Modeling was by A.P. and T.H. Data analysis and manuscript preparation was by L.D.G., P.J.B., T.H., and A.P.T.

**SUPPLEMENTAL INFORMATION**

Supplemental Information includes Supplemental Experimental Procedures, five figures, and two tables and can be found with this article online at http://dx.doi.org/10.1016/j.celrep.2014.10.033.

**AUTHOR CONTRIBUTIONS**

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