Ca$^{2+}$ release via IP$_3$Rs increases RyR mediated Ca$^{2+}$ spark frequency in ventricular cardiomyocytes without altering spark amplitude and duration

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Abstract

Calcium plays critical roles in cardiac cells, coupling electrical excitation to mechanical contraction with each heartbeat, while simultaneously mediating biochemical signals that regulate cell growth. While ryanodine receptors (RyRs) are fundamental to generation of elementary calcium release events (sparks) and global calcium elevations that underlie excitation-contraction coupling (ECC), calcium release via inositol 1,4,5-trisphosphate receptors (IP$_3$Rs) is also reported in cardiomyocytes. IP$_3$R calcium release modifies ECC as well as contributing to downstream regulation of hypertrophic gene expression. Recent studies suggest that proximal localisation of IP$_3$Rs with RyRs contributes to their ability to modify Ca$^{2+}$ handling during ECC. Here we aim to determine the mechanism by which IP$_3$Rs modify Ca$^{2+}$ handling in cardiomyocytes. We develop a mathematical model incorporating the stochastic behaviour of receptor opening that allows for the parametric tuning of the system to reveal the impact of IP$_3$Rs on spark activation. By testing multiple spark initiation mechanisms, we find that Ca$^{2+}$ release via IP$_3$Rs result in increased propensity for spark initiation within the cardiac dyad. Our simulations suggest that opening of IP$_3$Rs elevates Ca$^{2+}$ within the dyad, which increase the probability of spark initiation. Finally, we find that while increasing the number of IP$_3$Rs increases the probability of spark formation, it has little effect on spark amplitude, duration, or overall shape. Our study therefore suggests that IP$_3$R play a critical role in modulating Ca$^{2+}$ signaling for excitation contraction coupling

Author summary

While Ca$^{2+}$ release through ryanodine receptors (RyRs) initiates contraction in cardiomyocytes, the role of inositol 1,4,5-trisphosphate receptors (IP$_3$Rs) in
cardiomyocytes is less clear with Ca\(^{2+}\) release through these channels being invoked in regulating ECC and hypertrophic signalling. RyRs generate cytosolic Ca\(^{2+}\) signals through elemental Ca\(^{2+}\) release events called sparks. The mechanisms by which IP\(_3\)Rs influence cytosolic Ca\(^{2+}\) are not well understood. We created a 1D model of calcium spark formation in a cardiomyocyte dyad—the primary site of elemental RyR-based calcium release. We investigated possible behaviours of IP\(_3\)Rs and their interaction with RyRs in generating Ca\(^{2+}\) sparks. We show that for high IP\(_3\) concentration, a large number of IP\(_3\)Rs and high IP\(_3\)R affinity are required to noticeably affect spark shape. At lower IP\(_3\) concentration IP\(_3\)Rs can increase Ca\(^{2+}\) spark activity, but do not significantly alter the spark shape. Finally our simulations suggest that spark frequency can be reliably increased when IP\(_3\)Rs activity is such that a small continuous Ca\(^{2+}\) flux is introduced to the dyad to elevate Ca\(^{2+}\), and not via brief but high Ca\(^{2+}\) release from these receptors.

Introduction

Calcium plays a fundamentally important role in the regulation of each heartbeat. Ca\(^{2+}\) flux through L-type Ca\(^{2+}\) channels (LTCC) couples electrical activation to muscle contraction through excitation-contraction coupling (ECC) [1, 2]. Membrane depolarisation triggers a small influx of calcium through voltage-gated LTCCs (Fig. 1A) into 10-15 nm wide calcium microdomains [3, 4] called dyads. In these regions, LTCC channels are juxtaposed with a set of Ca\(^{2+}\) channels called ryanodine receptors (RyRs) on the intracellular sarcoplasmic reticulum (SR) compartment. RyRs are sensitised by the Ca\(^{2+}\) influx and release a larger amount of Ca\(^{2+}\) from the SR. This local Ca\(^{2+}\) release event at the dyad is known as a calcium spark (Fig. 1B) and cardiac contraction is determined by the sum of these elementary local Ca\(^{2+}\) release events at the many dyads regularly distributed through the cardiomyocyte volume.

In a majority of cell types, neurohormonal stimulation of intracellular Ca\(^{2+}\) is mediated by inositol 1,4,5-trisphosphate (IP\(_3\)) and IP\(_3\) receptors (IP\(_3\)Rs) located on the endoplasmic reticulum (ER) [5]. In cardiomyocytes, activation of G-protein coupled receptors (GPCRs) for neurotransmitters such as endothelin-1 (ET-1) and angiotensin-II (AngII) leads to elevation of IP\(_3\) and Ca\(^{2+}\) release via IP\(_3\)Rs [6–9]. Crosstalk between IP\(_3\)Rs and RyRs, in which activation of IP\(_3\)Rs via elevated IP\(_3\) leads to recruitment of neighbouring RyRs receptors, leading to larger Ca\(^{2+}\) release, was first suggested in smooth muscle cells [10]. Similar interaction between IP\(_3\)Rs and RyRs has also been proposed in embryonic myocytes [11, 12], atrial cardiac myocytes [13–15], spontaneously hypertensive rat (SHR) myocytes [8], and rabbit ventricular myocytes [16]. Given the lower abundance and Ca\(^{2+}\) flux of IP\(_3\)Rs relative to RyRs, how they can affect ECC remains poorly understood. In particular, the characteristics of IP\(_3\)R gating that may lead to recruitment of RyR receptors also remains to be determined.

Experimental investigations [17] and computational models [18, 19] of Ca\(^{2+}\) sparks have elucidated the role of the spatial distribution and density of RyR channels, and their stochastic interactions, in determining the spatio-temporal characteristics of Ca\(^{2+}\) sparks in health and disease [20]. IP\(_3\)Rs are proposed to collocate with RyRs [8, 16, 21–23] and are also known to exhibit increased expression in pathological conditions [24], here we use computational modelling to test a hypothesis that IP\(_3\)R Ca\(^{2+}\) release modulates Ca\(^{2+}\) spark activity, and thereby affects cytosolic Ca\(^{2+}\) and ECC.

Previously, stochastic and deterministic models have been developed which investigate the properties of RyRs in generating Ca\(^{2+}\) sparks [18, 25–30]. Computational models of IP\(_3\)Rs have also been developed primarily for various cell types where IP\(_3\)Rs are the predominant intracellular Ca\(^{2+}\) release channel [31–35]. Deterministic temporal
models have been proposed that include both IP$_3$Rs and RyRs, but do not provide information about sparks or spatial interactions between these two SR Ca$^{2+}$ release channels [36,37]. To date, the role of IP$_3$Rs in Ca$^{2+}$ spark formation, including both RyR and IP$_3$Rs in a stochastic computational model, has not been investigated. In this study, we investigate the influence that IP$_3$R activation may have in the shape and temporal behavior of Ca$^{2+}$ sparks through stochastic interaction between IP$_3$Rs and RyRs. We creates a 1D spatial model of cardiomyocyte dyads containing stochastically opening RyR and IP$_3$Rs. Using this model, we examine how Ca$^{2+}$-mediated interaction (crosstalk) between IP$_3$R and RyR channels impacts the spatio-temporal profile of the Ca$^{2+}$ spark. We investigate the sensitivity of spark initiation and shape to a range of IP$_3$R gating parameters and IP$_3$ concentration. Our findings suggest that for low IP$_3$ concentrations, Ca$^{2+}$ release via IP$_3$Rs is insufficient to initiate sparks but they increase the probability of spark events without changing spark shape. The model also suggests that a small sustained Ca$^{2+}$ flux from active IP$_3$Rs diffusing to neighbouring RyRs can trigger spark formation.

**Materials and methods**

**Model formulation**

We model the transport of Ca$^{2+}$ as a reaction-diffusion system that describes the movement of Ca$^{2+}$ in three compartments: cytosolic (Ca$_c$); junctional sarcoplasmic reticulum (Ca$_{JSR}$); and network sarcoplasmic reticulum (Ca$_{NSR}$):

$$\frac{\partial [Ca_c]}{\partial t} = D_c \nabla^2 [Ca_c] + J_{\text{buff}} - J_{\text{SERCA}} + J_{\text{release}}$$  \hspace{1cm} (1)

$$\frac{\partial [Ca_{JSR}]}{\partial t} = \beta_{JSR}(-J_{\text{release}} + J_{\text{refill}})$$  \hspace{1cm} (2)

$$\frac{\partial [Ca_{NSR}]}{\partial t} = D_{NSR} \nabla^2 [Ca_{NSR}] + J_{\text{SERCA}} - J_{\text{refill}},$$  \hspace{1cm} (3)

where $D_c$ and $D_{NSR}$ represent the Ca$^{2+}$ diffusivities in the cytosol and the network SR respectively (the junctional SR is assumed to be a small and hence well-mixed volume). $\beta_{JSR}$ represents the calsequestrin buffer, which is modelled following the approach of Keizer *et al.* [38]. $J_{\text{SERCA}}$ represents the flux of Ca$^{2+}$ from the cytosol into the NSR through the sarco-endoplasmic reticular Ca$^{2+}$-ATPase (SERCA) pumps. $J_{\text{refill}}$
represents the flux of Ca\(^{2+}\) refilling the JSR compartment from the NSR. \(J_{\text{buff}}\) is the flux of Ca\(^{2+}\) as it binds and unbinds to buffers in the cytosol. \(J_{\text{release}}\) represents the flux of Ca\(^{2+}\) from the JSR into the cytosol through RyRs and IP\(_3\)Rs, and is defined such that

\[
J_{\text{release}} = (g_{\text{RyR}} \cdot \text{RyR}_{\text{open}} + g_{\text{IP}_3 \text{R}} \cdot \text{IP}_3 \text{R}_{\text{open}}) \cdot (\text{Ca}_{\text{JSR}} - \text{Ca}_c),
\]

where RyR\(_{\text{open}}\) and IP\(_3\)R\(_{\text{open}}\) represent the number of open RyRs and IP\(_3\)Rs, respectively. RyR\(_{\text{open}}\) is calculated using a re-scaled stochastic model as proposed by Cannell et al. [18]. IP\(_3\)R\(_{\text{open}}\) is calculated based on the stochastic two-state 'park-drive' model proposed by Siekmann et al. [34] based on fitting single channel data [39, 40], as implemented by Cao et al. [35]. \(g_{\text{RyR}}, g_{\text{IP}_3 \text{R}}\) represent RyR and IP\(_3\)R flux coefficients.

\[\begin{align*}
\frac{\partial [B_m]}{\partial t} &= DB_m \nabla^2 [B_m] + k_{\text{on}}^m [B_m][\text{Ca}] - k_{\text{off}}^m [\text{Ca}B_m] \\
\frac{\partial [B_{im}]}{\partial t} &= k_{\text{on}}^{im} [B_{im}][\text{Ca}] - k_{\text{off}}^{im} [\text{Ca}B_{im}],
\end{align*}\]

where \(k_{\text{on}}^m\) and \(k_{\text{off}}^m\) represent the on and off rates for mobile buffers (ATP, CaM or Fluo4), and \(k_{\text{on}}^{im}\) and \(k_{\text{off}}^{im}\) are the on and off rate for the immobile buffer (TnC). Further expressions and model details may be found in the Supplementary Text S1.

Fig 2. Diagram of 1D model settings: (A) Model fluxes and compartments, (B) Spatial settings of the dyad. SERCA is positioned outside JSR location.

**Numerical implementation**

We simulated the reaction-diffusion system and stochastic interactions between RyR and IP\(_3\)Rs within a single dyad on a 1D geometry to reflect the experimental line-scan recording of calcium sparks and transients. This reduced-order representation enabled an investigation into the influence of IP\(_3\)Rs on Ca\(^{2+}\) spark generation in the dyad. This
choice of representation was further justified by previous detailed 3D simulations of Ca\(^{2+}\) spark generation, which showed that the spatial distribution of RyRs on the dyad was not critical to the spark profile when the number of RyRs in the cluster was greater than 9 [41].

The spatial settings for each cell compartment and receptors along this 1D geometry are illustrated in Fig. 2B. The 0.2 \(\mu\)m-wide dyad has 45 RyRs positioned on either side of the midline, separated by 0.04 \(\mu\)m, with a variable number of IP\(_3\)Rs placed another 0.04 \(\mu\)m from the centre at both ends of the dyad.

The partial differential equations (PDEs) were discretized in space using a finite difference scheme. The resulting system of ODEs was solved using a first-order Runge-Kutta method with a maximum time step \(dt = 1 \times 10^{-4}\) ms and a spatial step \(dx = 0.04\) \(\mu\)m. Stochastic IP\(_3\)R and RyR gating states were solved using a hybrid Gillespie method. All software was written using Matlab2017b (The MathWorks Inc., Natick, Massachusetts).

**Results**

We tested the sensitivity of the Ca\(^{2+}\) spark profile to interactions between IP\(_3\)Rs and RyRs by comparing sparks with no IP\(_3\)Rs to sparks generated with different numbers of IP\(_3\)Rs and varying parameter settings. Specifically, we investigated the dependence of amplitude, duration and frequency of spark events to: number of IP\(_3\)Rs; IP\(_3\)R Ca\(^{2+}\)-sensitivity; and IP\(_3\) concentration.

**Number of IP\(_3\)Rs per dyad does not affect the shape of LTCC-initiated Ca\(^{2+}\) sparks**

To determine the effects of IP\(_3\)R-mediated Ca\(^{2+}\) release on the shape of the Ca\(^{2+}\) spark, single spark events were initiated within a dyad by opening 30 RyRs per cluster at \(t = 0\) ms, with different numbers of IP\(_3\)Rs: 0, 5, 10, or 20 per cluster (yellow box, Fig. 2B). Simulations were run for \(T_{obs} = 80\) ms, and each simulation was repeated 108 times. Example simulation outputs are given in Supplementary Figures 1 and 2. Representative fluorescence trace, and means and 95% confidence intervals for Ca\(^{2+}\) concentration in the JSR at the RyR locations, and IP\(_3\)Rs and RyR receptor open populations, are provided in Fig. 3. These simulation results show that LTCC-triggered sparks (Fig. 3, first column) are similar in shape and duration irrespective of the number of IP\(_3\)Rs.

Additionally, in all simulations, minimum \([\text{Ca}^{2+}]_{\text{JSR}}\) was \(\approx 200\) \(\mu\)M at \(\approx 50\) ms, which coincides with the time RyRs start to close. This is consistent with the hypothesis that spark termination is related to \([\text{Ca}^{2+}]_{\text{JSR}}\) depletion, as suggested previously [42, 43]. IP\(_3\)Rs were active primarily at the start of simulations (Fig. 3, third column) when only \(\approx 20\%\) of IP\(_3\)Rs were open. However, RyRs fluctuated to \(\approx 45\%\) of RyRs for \(\approx 50\) ms and closed at \(\approx 60\) ms (Fig. 3, fourth column). This suggests that RyRs, but not IP\(_3\)Rs, primarily determine spark shape. Since IP\(_3\)Rs are mostly active at the beginning of simulations, they may however play a role in spark initiation.

**IP\(_3\)Rs can facilitate spark initiation**

To test the role that IP\(_3\)Rs play in spark activation, we next considered which dyad trigger settings were sufficient to generate a spark. Experiments on cardiac and smooth muscle cells suggested that IP\(_3\)Rs may not create a spark by themselves, but can facilitate neighbouring RyR opening [10, 12, 13]. Therefore we tested how one dyad will behave when: (a) no initiation is applied; (b) 5 IP\(_3\)Rs are opened at \(t = 0\) ms; (c) 5
Fig 3. Initiated spark shape is not affected by number of IP$_3$Rs. Profiles for sparks initiated by opening RyR channels at $t = 0$ ms, with different numbers of IP$_3$Rs per cluster: (A) 0, (B) 5, (C) 10, (D) 20 IP$_3$Rs. Panels show mean and 95% confidence intervals ($\mu \pm 1.96\sigma$) from 108 simulations, from left to right: fluorescence trace, $[\text{Ca}^{2+}]_{\text{SR}}$ at the RyR positions, number of opened IP$_3$Rs and number of opened RyRs.

RyRs are opened at $t = 0$ ms; (d) 5 IP$_3$Rs and 2 RyRs are opened at $t = 0$ ms; and (e) consistently open IP$_3$Rs (IP$_3$R “leakage”).

Simulation results shown in Fig. 3 do not show significant variability in spark shape with different number of IP$_3$Rs, therefore we fixed the number of IP$_3$Rs to 20. Simulations were run for $T_{\text{obs}} = 80$ ms and repeated 108 times, for each of these 5 triggering mechanisms. We calculated the percentage of simulations which showed sparks (we assumed a spark to have occurred if max($\Delta F/F_0$) > 1), and spark initiation times (when the maximum value of the fluorescence trace occurred) within each simulation. Results shown in Fig. 4 indicate that both the percentage of simulations that depict spark initiation (Fig. 4A) and the spark initiation times within a simulation (Fig. 4B) depend on the trigger mechanism. Simulations with (a) no trigger, (b) 5 opened IP$_3$Rs, and (d) mixture of opened receptors, showed sparks in only $\approx 12\%$, $\approx 23\%$ and $\approx 32\%$ of runs, respectively (Fig. 4A). Furthermore, the small number of sparks and the broad distribution of their time to peak (Fig. 4B) suggests that in each of these cases spark initiation occurred at a random time following channel opening. Nevertheless spark amplitudes were approximately the same in these simulations (shown in Supplementary Figure 3). These results indicate that intermittently opening IP$_3$Rs increases the probability of spark initiation but may not reliably initiate a spark under fixed IP$_3$ concentration (0.15 $\mu$M).

Simulations with (c) 5 opened RyRs and (e) leaking IP$_3$Rs showed spark initiation...
Fig 4. IP$_3$Rs increase propensity for spontaneous Ca$^{2+}$ sparks. Simulation results using different triggers. (A) Percentage of 108 runs that had max $\Delta$CaF$^4$/CaF$^4_0 > 1$ under different triggering mechanisms mentioned above. (B) Times when maximum values of the trace were reached. (C) Mean and 95% confidence intervals ($\mu \pm 1.96\sigma$) of simulations under 5 opened RyRs at $t = 0$ ms (top) and leaking IP$_3$R (bottom). Columns illustrate averaged fluorescence trace of reacted runs, Ca$_{JSR}$ concentration at the RyR locations, number of opened IP$_3$Rs and number of opened RyRs (from right to left, respectively).

in almost all simulation runs. However, there was a difference in the distributions of spark initiation times (Fig. 4B): (c) 5 opened RyRs resulted in almost instantaneous spark initiation, while IP$_3$R “leakage” increased the frequency of sparks, but spark initiation times were distributed more widely. Fig. 4B suggests that opening RyRs (c) instantaneously initiates sparks, while highly active IP$_3$Rs facilitate spark formation by priming RyRs for activation thereby increasing their likelihood for spontaneous opening (e).

“Leaking” IP$_3$Rs showed more broadly distributed spark initiation times, indicated in the much wider confidence intervals in bottom plots of Fig. 4C. Furthermore, the time to initiation was longer compared to the opened RyR case (Fig. 4C, first column). Decay but not recovery of [Ca$^{2+}$]$_{JSR}$ can be seen in averaged results (second column, Fig. 4C). These observations again indicate that Ca$^{2+}$ sparks were initiated spontaneously with IP$_3$R activated slow Ca$^{2+}$ release.

**IP$_3$R open probability influences spark shape**

Cardiomyocytes express three isoforms of IP$_3$R: IP$_3$R1, IP$_3$R2 and IP$_3$R3 [21,44,45]. Type 2 isoform is predominant [21] and has the highest IP$_3$ binding affinity, followed by type 1 and type 3 being the least sensitive to IP$_3$. As mathematical models using the type 1 isoform are more developed, in simulations up to this point we used parameter values in the IP$_3$R model that had previously been fitted to single channel recordings on
type 1 IP₃ receptors [46]. To explore the influence of the Ca²⁺-sensitivity of different IP₃Rs isoforms we shifted the Ca²⁺-sensitivity curve (supplementary Figure 7) to give qualitative estimates of the different isoforms provided in the experimental literature [34,47].

Simulations with type 2 receptor parameters and varying number of IP₃Rs are shown in Fig. 5 for [IP₃] = 0.15 µM. Sparks were initiated by opening 5 RyRs at t = 0 ms. It can be seen that, as for type 1 parameters, spark amplitudes were not affected by the number of receptors (Fig. 5A). However, unlike type 1 simulations, type 2 parameters showed an increase in spark duration under higher number of IP₃Rs (Fig. 5B). This difference may be due to type 1 parameter simulations showing the number of opened IP₃Rs to be highest at t = 0 ms and decreasing subsequently throughout the simulation (Fig. 3), while for type 2 parameters IP₃Rs are initially closed over the first t = 5 ms, and may open again subsequently during the simulation (Fig. 5C). This difference is in particular evident for simulations with 20 IP₃Rs, when type 2 parameters showed on average 1 opened IP₃R after t = 10 ms, while for type 1 parameters all IP₃Rs are on average closed by this point (Fig. 5D).

High [IP₃] increases robustness of spark initiation

IP₃R behaviour depends on cytosolic Ca²⁺ and IP₃ concentrations [47]. Increased [IP₃] overcomes Ca²⁺ dependent inhibition, which could be a factor in the dyadic environment. Therefore we next investigated spark triggering mechanisms and spark shape with 20 IP₃Rs at 6 different IP₃ concentrations ranging from 0.05 µM to 3 µM. As in previous simulations, we calculate the percentage of simulations in which a spark was initiated, as well as the spark initiation time (time to maximum of the fluorescence trace) and spark shape.

Table 1 shows the percentage of simulation runs in which a spark was initiated, for [IP₃] = 0.05; 0.15; 0.5; 1; 2; 3 µM. In these simulations IP₃R type 1 parameters were used, and different triggering mechanisms were considered, as in previous simulations. For “leaking” IP₃Rs as well as simulations triggered with opened RyRs, reliable spark initiation occurred for all IP₃ concentrations. For simulations triggered with IP₃R opening, the probability of successful spark generation increased with increasing IP₃ concentration.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>[IP₃] 0.05 µM</th>
<th>0.15 µM</th>
<th>0.5 µM</th>
<th>1 µM</th>
<th>2 µM</th>
<th>3 µM</th>
</tr>
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<tbody>
<tr>
<td>(b) 5 open IP₃Rs</td>
<td>17</td>
<td>23</td>
<td>54</td>
<td>86</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>(c) 5 open RyRs</td>
<td>99</td>
<td>97</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>(e) Leaking IP₃Rs</td>
<td>99</td>
<td>100</td>
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Table 1. Percentage of simulations with detected sparks under different IP₃ concentration and triggering mechanisms. Percentages were calculated from 108 simulations with T_{obs} = 80 ms and 20 IP₃Rs. Triggering mechanism and IP₃ concentration are provided in rows and columns, respectively.

Summaries of spark shape and spark initiation times for these triggering mechanisms under different IP₃ concentrations are shown in Fig. 6. Full simulation summaries are provided in Supplementary Figures 4-6. For simulations triggered by opened RyRs, spark times are not strongly affected by IP₃ alterations, however for opened IP₃Rs and “leaking” IP₃Rs, more robust spark initiation times are observed under higher IP₃ concentration (Fig. 6A). Spark amplitudes remained similar under all IP₃ concentrations (Fig. 6B), showing only modest increase with increasing [IP₃]. These
Fig 5. The number of IP₃Rs can alter spark duration in type 2 receptors. Summaries of 108 simulations using varying numbers of IP₃Rs. (A) Spark amplitudes, (B) spark duration, (C) Simulation summaries (means and 95% confidence intervals) under 5 and 10 IP₃Rs per cluster. From left to right: fluorescence trace, [Ca²⁺]_{JSR} at the RyR positions, number of opened IP₃Rs and number of opened RyRs. [IP₃] was set to 0.15 µM. (D) Comparison of type 2 and type 1 IP₃Rs simulations under 20 IP₃Rs per cluster and [IP₃] = 0.15 µM. RyR receptors were forcefully opened at t = 0. Spark duration is increased by type 2 IP₃Rs but not type 1.

Observations confirm that for IP₃R type 1 parameters, spark properties are determined predominantly by RyR activity.

Finally, we compared simulations for type 1 and type 2 parameter sets at different [IP₃], shown in Fig. 7. A more detailed summary of effect of different [IP₃] on spark shape and initiation times in simulations with type 2 parameter set are provided in Supplementary Figure 8. As illustrated by the third column of Fig. 7, IP₃R activity increases with higher [IP₃] under both parameter sets. For type 1 parameters, IP₃Rs showed highest activity at t ≈ 5 ms after which receptors within the cluster started to close, while for type 2 parameters IP₃Rs were continuously open under higher [IP₃]. This difference influences RyR behaviour and hence spark duration (red boxes in Fig. 7).
Fig 6. Increasing [IP$_3$] makes spark initiation more robust. 108 simulations summaries using different [IP$_3$]. (A) Times when maximum values of the trace were reached; (B) Spark amplitudes. Full simulation summaries are provided in Supplementary Figures 4-6. All simulations were run for $T_{obs} = 80$ ms and 20 IP$_3$Rs.

Discussion

IP$_3$Rs are expressed in cardiomyocytes, where they colocalise with RyRs in dyads, yet a functional role in Ca$^{2+}$ spark formation – elementary Ca$^{2+}$ events underlying cardiac ECC – is unclear, in part because of the dominance of RyR Ca$^{2+}$ release. In this study, we have sought to determine the potential for IP$_3$R Ca$^{2+}$ release to contribute to spark formation in the cardiomyocyte dyad. We developed a 1D spatial model accounting for stochastic RyR and IP$_3$R gating and examined spark initiation in a single dyad. Specifically, we investigated whether IP$_3$Rs in a dyad can affect spark initiation and shape and how this changes depending on modelled IP$_3$R gating behaviour.

Model assumptions and their implications

In our model we made two major assumptions: 1) SR receptors are in close proximity to each other, but they do not overlap, and 2) there is no Ca$^{2+}$ diffusion in the JSR compartment. If receptors overlap, then Ca$^{2+}$ depletion in the JSR could occur more quickly due to the larger Ca$^{2+}$ flux through the SR receptors. This overlap could subsequently cause spark termination and reduce spark duration. Ca$^{2+}$ diffusion in the JSR may also change spark duration by affecting Ca$^{2+}$ depletion in the SR. However Cannell et al. [18] showed that the physical distribution of RyRs within the dyad will not greatly affect the spark profile in clusters greater than 9 RyRs. Walker et al. [48] also showed that the propensity of spark formation from stochastic release of Ca$^{2+}$ from ion channels increased with larger and denser clusters of RyRs. Furthermore, our study shows that IP$_3$R activation also does not alter spark profile.
Fig 7. Comparison of type 1 and type 2 parameter simulations under varying $[\text{IP}_3]$. Mean and 95% confidence intervals ($\mu \pm 1.96\sigma$) of simulations under type 1 (top) and type 2 (bottom) parameter sets. Columns illustrate averaged fluorescence trace of reacted runs, $[\text{Ca}^{2+}]_{\text{SR}}$ concentration at the RyR locations, number of opened IP$_3$Rs and number of opened RyRs (from right to left, respectively). All simulations were run for $T_{\text{obs}} = 80$ ms and with 20 IP$_3$Rs.

Our simulations support the idea that Ca$^{2+}$ via IP$_3$R prime RyRs for ECC in disease.

Our results indicate that for type 1 IP$_3$R, the number of IP$_3$Rs in a cluster does not significantly affect spark shape when triggered by the L-type channel Ca$^{2+}$ flux. This implies that, in healthy cardiac cells, sparks are insensitive to the relatively small perturbations caused by IP$_3$R opening. However, IP$_3$R expression increases significantly in diseased cardiomyocytes [8, 44]. Increasing numbers of IP$_3$Rs and in particular ‘leaky’ IP$_3$Rs, as would result from increased diastolic Ca$^{2+}$ concentration, lead to increased spark initiation frequency. This suggests that the increase in IP$_3$R expression could be a compensatory mechanism to dyad uncoupling from electrical activity in disease [49].
In the absence of Ca\(^{2+}\) influx through the LTCC, however, our analysis indicated that prolonged IP\(_3\)R “leakage” was able to initiate a spontaneous spark, while intermittently opening IP\(_3\)Rs were not sufficient to reliably trigger a spark (figure 4A). These results agree with a range of experiments in cardiac cells \([10,12,13]\) reporting that opened IP\(_3\)Rs do not provide sufficient Ca\(^{2+}\) to trigger an event, however their activation can sensitize neighbouring RyR clusters. In hypertrophic rat cardiomyocytes and in atrial cells, IP\(_3\)R channels have been been shown to increase diastolic [Ca\(^{2+}\)] \([50]\). Our simulations imply that this rise in diastolic [Ca\(^{2+}\)] can directly cause the increase in spontaneous calcium transients that is also observed in hypertrophic cells \([50,51]\).

“Leaky” IP\(_3\)R in our simulations represented a type of spark trigger where IP\(_3\)R channels were constitutively open. While ion channels do not physiologically remain constitutively open it is plausible that the “leak” may represent the elevation in Ca\(^{2+}\) arising from several intermittently opening and closing IP\(_3\)Rs during ECC.

Our simulations indicate that increasing [IP\(_3\)] can make spark initiation more robust and also slightly increase spark duration (Fig. 6). However, spark amplitudes remained similar under investigated [IP\(_3\)] (Fig. 6B). Specifically, our simulations agree with previous findings in mouse and rabbit ventricular myocytes \([16,51]\) which found no significant changes in amplitude immediately after addition of 10 µM IP\(_3\). However, Domeier et al. \([16]\) indicated that the amplitude of the sparks may change in longer duration experiments (after \(\approx 7\) min following IP\(_3\) application). The authors also suggested that IP\(_3\) application did not affect spark duration, while our simulations generated slightly longer sparks under 2 µM IP\(_3\) compared to 0.05 µM IP\(_3\) concentration. It should be noted that Domeier et al. \([16]\) used imaging resolution of 3 ms per scan, while in our simulations the time resolution was set to 0.0001 ms.

The potential roles of different isoforms of IP\(_3\)R

We based our IP\(_3\)R model on the Siekmann et al. stochastic two-state park-drive model \([35,46]\) to simulate IP\(_3\)R induced calcium release. This model was parametrised for type 1 IP\(_3\)Rs with the Ca\(^{2+}\) sensitivity ranging between 0.1 µM and 10 µM (see Supplementary Figure 7). This sensitivity was measured in type I IP\(_3\)R channels expressed in COS cells \([?]\). To investigate type 2 IP\(_3\)R behaviour, we altered model parameters to qualitatively represent Ca\(^{2+}\)-sensitivity curve as provided in \([34,47]\). The type 2 IP\(_3\)Rs are sensitive to Ca\(^{2+}\) in the range 0.01 µM to 1 µM (see Supplementary Figure 7).

Our simulations suggest that type-2 IP\(_3\)Rs would alter the shape of the Ca\(^{2+}\) spark by releasing Ca\(^{2+}\) at the early rise phase as well as the late decay phase of the spark timeline. While this is surprising, given the wide range of Ca\(^{2+}\) sensitivities reported \([?]\) even for one IP\(_3\)R isoform type in experiments, it is unclear what the specific parameters for IP\(_3\)Rs for Ca\(^{2+}\) sensitivity should be. In addition, the 1D dyadic simulations here do not include structural details that have been shown to produce Ca\(^{2+}\) concentrations within the dyad of 6 - 10 µM \([52,53]\). Therefore, both types of IP\(_3\)Rs may actually be inhibited by a high concentration of calcium within the dyad during Ca\(^{2+}\) spark events. This would mean that neither IP\(_3\)R isoform would affect spark shape but the sensitising effect would remain. Additionally, IP\(_3\) sensitivity is suggested to vary between isoforms \([?]\). Further work needs to be done to incorporate more spatial detail of the collocation of IP\(_3\)Rs and RyRs as well as the isoform differences to further test the validity of our type 2 isoform predictions in this study.
Conclusion

IP₃Rs may not affect spark initiation or shape in healthy cells with coupled RyRs and LTCC. In the absence of LTCC trigger, however, we tested 5 different initiation cases and showed that Ca²⁺ release via IP₃R can trigger sparks by sensitizing neighbouring RyR clusters.

Further work is needed in order to link these findings on IP₃Rs-influenced spark formation to models of IP₃ signalling in cardiomyocytes [54,55], and multi-scale integration of stochastic spark formation to understand how this impacts on global cytosolic Ca²⁺ transient dynamics and excitation-contraction coupling under normal and disease conditions [56,57].

Supporting information

S1 Text: Model equations, parameters and references.

S2 Figures: Supplementary figures for single dyad simulations.

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References


