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Ana Maria Gómez, Heping Cheng, W Jonathan Lederer, Donald M. Bers. Ca2+ Diffusion and Sarcoplasmic Reticulum Transport Both Contribute to [Ca2+]i Decline During Ca2+ Sparks in Rat Ventricular Myocytes. The Journal of Physiology, 1996, 496, pp.575 - 581. 10.1113/jphysiol.1996.sp021708 . inserm-02477361

HAL Id: inserm-02477361

https://inserm.hal.science/inserm-02477361

Submitted on 13 Feb 2020

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Ca^{2+} diffusion and sarcoplasmic reticulum transport both contribute to $[Ca^{2+}]_i$ decline during Ca^{2+} sparks in rat ventricular myocytes

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1. We sought to evaluate the contribution of the sarcoplasmic reticulum (SR) Ca^{2+} pump (*vs.* diffusion) to the kinetics of $[Ca^{2+}]_i$ decline during Ca^{2+} sparks, which are due to spontaneous local SR Ca^{2+} release, in isolated rat ventricular myocytes measured using fluo-3 and laser scanning confocal microscopy.

2. Resting Ca^{2+} sparks were compared before (control) and after the SR Ca^{2+}-ATPase was either completely blocked by 5 μM thapsigargin (TG) or stimulated by isoprenaline. Na^+–Ca^{2+} exchange was blocked using Na^+-free, Ca^{2+}-free solution (0 Na^+, 0 Ca^{2+}) and conditions were arranged so that the SR Ca^{2+} content was the same under all conditions when Ca^{2+} sparks were measured.

3. The control Ca^{2+} spark amplitude (281 ± 13 nM) was not changed by TG (270 ± 21 nM) or isoprenaline (302 ± 10 nM). However, the time constant of $[Ca^{2+}]_i$ decline was significantly slower in the presence of TG (29·3 ± 4·3 ms) compared with control (21·6 ± 1·5 ms) and faster with isoprenaline (14·5 ± 0·9 ms), but in all cases was much faster than the global $[Ca^{2+}]_i$ decline during a control twitch (177 ± 10 ms).

4. The spatial spread of Ca^{2+} during the Ca^{2+} spark was also influenced by the SR Ca^{2+} pump. The apparent 'space constant' of the Ca^{2+} sparks was longest when the SR Ca^{2+} pump was blocked, intermediate in control and shortest with isoprenaline.

5. We conclude that while Ca^{2+} diffusion from the source of Ca^{2+} release is the dominant process in local $[Ca^{2+}]_i$ decline during the Ca^{2+} spark, Ca^{2+} transport by the SR contributes significantly to both the kinetics and spatial distribution of $[Ca^{2+}]_i$ during the Ca^{2+} spark.

Ca^{2+} sparks are produced when Ca^{2+} release channels in the sarcoplasmic reticulum (SR) open spontaneously or are triggered to open by a local increase in $[Ca^{2+}]_i$ (Cheng, Lederer & Cannell, 1993; Cannell, Cheng & Lederer, 1994; López-López, Shacklock, Balke & Weir, 1994; Cannell, Cheng & Lederer, 1995; López-López, Shacklock, Balke & Weir, 1995). The duration of the Ca^{2+} spark reflects a balance of Ca^{2+} efflux from the SR through the ryanodine receptors (RyR) and several factors that can reduce local $[Ca^{2+}]_i$ (Cheng, Cannell & Lederer, 1995). Six factors could contribute to the decline of the Ca^{2+} spark: (1) closure of the SR Ca^{2+} release channel (i.e. RyR); (2) Ca^{2+} binding to buffers; (3) Ca^{2+} diffusion away from the release site in free solution or on buffers; (4) Ca^{2+} pumping back into the SR via the SR Ca^{2+}-ATPase; (5) Ca^{2+} accumulation by the mitochondria; and (6) Ca^{2+} extrusion from the cell by the Na^+–Ca^{2+} exchanger and sarcolemmal Ca^{2+}-ATPase.

Global elevation of $[Ca^{2+}]_i$, produced by a normal twitch $[Ca^{2+}]_i$ transient, arises as Ca^{2+} sparks are recruited by the activation of L-type Ca^{2+} channels (Cannell *et al.* 1994, 1995; López-López *et al.* 1995; Santana, Cheng, Gómez, Cannell & Lederer, 1996). Such global increases in $[Ca^{2+}]_i$ remove diffusion as a factor contributing to the fall of $[Ca^{2+}]_i$ because the spatial distribution of $[Ca^{2+}]_i$ is uniform (Cheng *et al.* 1995). In this situation, the dominant processes contributing to global $[Ca^{2+}]_i$ decline are SR Ca^{2+}-ATPase activity and the Na^+–Ca^{2+} exchange (Bassani, Bassani & Bers, 1994). In rat ventricular myocytes, the proportion of Ca^{2+} transported by the SR Ca^{2+} pump *vs.* that by Na^+–Ca^{2+} exchange during relaxation is about 92% *vs.* 7%, whereas in rabbit ventricular myocytes, owing to slower SR Ca^{2+} pumping and faster Na^+–Ca^{2+} exchange this is 70% *vs.* 28% (Bassani, Bassani & Bers, 1992, 1994; Negretti, O'Neill & Eisner, 1993). In contrast, the Ca^{2+} spark represents a local

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This manuscript was accepted as a Short Paper for rapid publication.

elevation of $[Ca^{2+}]_i$ which is free to diffuse from its site of origin to other regions of the cardiac myocyte where $[Ca^{2+}]$ is lower. Thus, the rapid decay of the Ca^{2+} spark (time constant, τ, ~25 ms) when compared with the global $[Ca^{2+}]_i$ transient (τ, ~200 ms) may arise largely from a diffusional component that only the Ca^{2+} spark has. However, as Ca^{2+} diffuses away from the release site it is subject to transport by the same Ca^{2+} transport systems mentioned above. In this paper we have investigated the role of SR Ca^{2+}-ATPase in the decline of the Ca^{2+} spark. We have made use of the specific inhibitor of SR Ca^{2+}-ATPase thapsigargin (Sagara, Fernadez-Belda, de Meis & Inesi, 1992). We examined Ca^{2+} sparks when SR Ca^{2+}-ATPase was completely inhibited, but without depleting the SR of Ca^{2+} (Bassani, Bassani & Bers, 1993; Bassani, Yuan & Bers, 1995). We also used isoprenaline to stimulate SR Ca^{2+}-ATPase via cyclic AMP and the phosphorylation of phospholamban (Tada, Kirchberger, Repke & Katz, 1974). The results indicate that either blocking or stimulating SR Ca^{2+}-ATPase significantly alters the kinetics of local $[Ca^{2+}]_i$ decline during a Ca^{2+} spark, as well as its spatial spread.

METHODS

Cells

Single ventricular cardiac myocytes were prepared from male, Sprague–Dawley rats (~2 months old) by standard methods (Cheng *et al.* 1993; Cannell *et al.* 1995). Briefly, animals were killed by an overdose of sodium pentobarbitone (100 mg kg^{-1} I.P.) after which hearts were quickly removed and perfused using the Langendorff method with a series of physiological solutions, including one that contained collagenase (Worthington, Type II; 1 mg ml^{-1}). Following isolation of single cells, extracellular $[Ca^{2+}]$ ($[Ca^{2+}]_o$) was increased to 1·0 mM and the cells were stored at room temperature (20–23 °C) until needed.

Measurement of $[Ca^{2+}]_i$

Cells were loaded with the Ca^{2+} indicator fluo-3 either by diffusion of the fluo-3 (100 μM) salt from the voltage-clamp pipette into the cell or by using the acetyoxymethyl (AM) ester derivative of fluo-3. This second method involves dissolving fluo-3 AM (50 μg) in 100 μl of a DMSO–Pluronic F-127 mixture (4 : 1 by weight) and incubating cells in a physiological saline containing 5 μM fluo-3 for 20 min and then allowing 15 min in physiological saline alone for de-esterification. Fluorescence was measured using a confocal microscope (see below) with 488 nm excitation from an argon ion laser (Cheng *et al.* 1993).

Images from the confocal microscope

A laser scanning confocal microscope (MRC 600; Biorad, Cambridge, MA, USA) with a ×63 magnification Zeiss Neofluar lens (numerical aperture, 1·25) was used to acquire fluorescence images. Two kinds of image were obtained, both with a resolution of 0·4 μm (in the horizontal plane) and 0·7 μm (in the vertical plane). Images of the whole cell in the x–y plane at full spatial resolution were obtained at 1 s^{-1}. Line-scan images were obtained at 500 s^{-1} but with resolution only along a single line (Cheng *et al.* 1993); these images were used for all of the kinetic data obtained here. Images were analysed using SOM and COMOS software (Biorad) and IDL (Research Systems Inc., Boulder, CO, USA).

The fluo-3 fluorescence was transformed to $[Ca^{2+}]_i$ by a pseudoratio method (Cheng *et al.* 1993; Cannell *et al.* 1994) using the following equation:

$$[Ca^{2+}]_i = \frac{K_d(F/F_0)}{(K_d/[Ca^{2+}]_{i,rest}) + 1 - (F/F_0)},$$

where K_d is the dissociation constant for fluo-3 (400 nM), F is the fluorescence intensity and F_0 is the intensity at rest at each position determined as the mean fluorescence intensity of the lowest fifty pixels along each time line. The $[Ca^{2+}]_i$ at rest ($[Ca^{2+}]_{i,rest}$) for this F_0 was assumed to be 100 nM.

Solutions

Changes in superfusion solutions were carried out in less than 3 s using a bath equipped for rapid solution change. Three basic solutions were used in our experiments. The normal Tyrode solution (NT) contained (mM): 140 NaCl, 5·4 KCl, 2 $CaCl_2$, 1 $MgCl_2$, 10 Hepes and 10 glucose, pH 7·4. The Na^+-free, Ca^{2+}-free (0 Na^+, 0 Ca^{2+}) solution was the same, except Na^+ was replaced by Li^+ and $CaCl_2$ was replaced by 1 mM EGTA. A Na^+-free solution (0 Na^+, 2 Ca^{2+}) had the same composition as NT, but Na^+ was replaced with equimolar Li^+. Thapsigargin (TG) was added from a 10 mM stock in DMSO to the appropriate solution immediately before use to give a final concentration of 5 μM. Caffeine and isoprenaline were added directly to the appropriate solution to produce final concentrations of 10 mM and 1 μM, respectively. In experiments that used patch clamping to control membrane potential (in whole-cell mode), the pipette-filling solution contained (mM): 60 CsCl, 60 KCl, 5 K_2ATP, 5 MgATP, 10 Hepes and 0·10 fluo-3, pH 7·2. Patch-clamp electrodes were pulled from 1·5 mm filamented thin-walled borosilicate glass capillaries (World Precision Instruments, New Haven, CT, USA). All experiments were carried out at room temperature.

Statistical comparisons were carried out using Student's t test or one-way analysis of variance. $P < 0·05$ was considered significant and n refers to the number of analysed Ca^{2+} sparks.

RESULTS

Protocol to allow assessment of Ca^{2+} sparks with SR Ca^{2+}-ATPase blockade by thapsigargin

To assess the contribution of SR Ca^{2+}-ATPase to the $[Ca^{2+}]_i$ decline during Ca^{2+} sparks we compared control Ca^{2+} sparks with those observed when SR Ca^{2+}-ATPase was completely blocked by TG. Comparison of Ca^{2+} sparks in the absence and presence of SR Ca^{2+}-ATPase requires two fundamental conditions. First, the SR Ca^{2+}-ATPase must be completely inhibited and second, Ca^{2+} sparks of comparable amplitude must be observable in the presence of Ca^{2+}-ATPase blockade. To achieve this we used the experimental strategy developed by Bassani *et al.* (1993, 1994, 1995), where SR Ca^{2+}-ATPase could be completely blocked without significantly changing the SR Ca^{2+} content. The results were obtained as follows.

After steady-state stimulation at 1 Hz, the amplitude of a caffeine (10 mM)-induced $[Ca^{2+}]_i$ transient in 0 Na^+, 0 Ca^{2+} solution was used to assess the SR Ca^{2+} content. Caffeine was washed away in NT and the cell returned to steady-state stimulation. Then stimulation was stopped and the cell

was superfused in 0 Na^+, 0 Ca^{2+} solution to abolish Ca^{2+} flux via Na^+–Ca^{2+} exchange and maintain constant SR Ca^{2+} load during rest. Control Ca^{2+} sparks were acquired and then the cell was exposed to 5 μM TG for 2 min (in 0 Na^+, 0 Ca^{2+} solution), which was sufficient to block completely the SR Ca^{2+} pump (Bassani *et al.* 1993, and see below). During this time resting $[Ca^{2+}]_i$ did not change. After Ca^{2+} pump blockade, Ca^{2+} sparks were again acquired in 0 Na^+, 0 Ca^{2+} solution for 1–2 min until the SR Ca^{2+} content was assessed by a second caffeine exposure in 0 Na^+, 0 Ca^{2+} solution.

After 2 min of TG treatment there was no significant decrease in the peak $[Ca^{2+}]_i$ during the caffeine-induced contracture (control, 1077 ± 187 nM; TG, 1087 ± 198 nM; see Fig. 1*A*). While the amplitude of caffeine-induced $[Ca^{2+}]_i$ transients in rat ventricular myocytes are generally not affected by the presence or absence of $[Na^+]_o$ (Bassani *et al.* 1994), 0 Na^+, 0 Ca^{2+} solution with caffeine was used to assess SR Ca^{2+} content in the present study. The time constant (τ) for decline of the caffeine-induced $[Ca^{2+}]_i$ transient was slower when Na^+–Ca^{2+} exchange was blocked

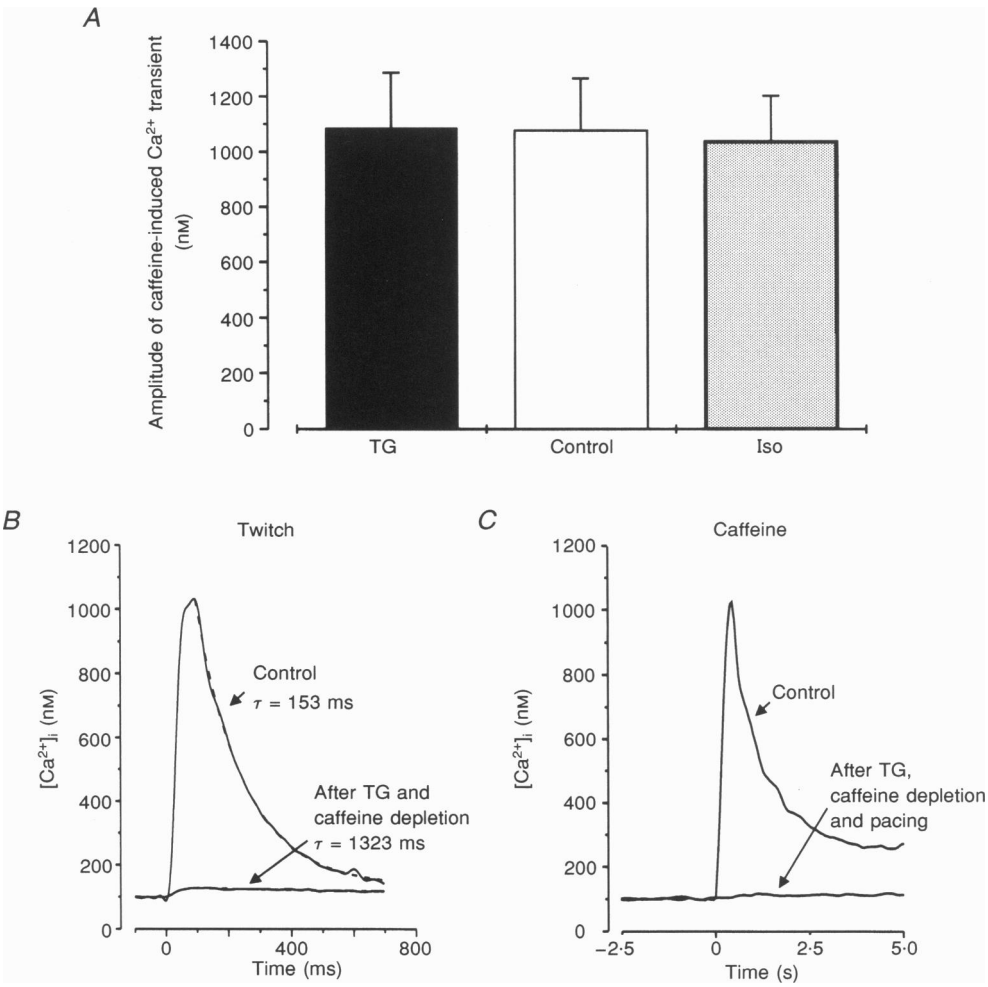


Figure 1. SR Ca^{2+} content and twitch $[Ca^{2+}]_i$ transients before and after thapsigargin

A, SR Ca^{2+} content assessed as the amplitude of the $[Ca^{2+}]_i$ transient induced by rapid exposure to 10 mM caffeine under the 3 conditions used to measure Ca^{2+} sparks. Thapsigargin (TG) values were obtained after 1 Hz steady-state stimulation and 2 min of rest in 0 Na^+, 0 Ca^{2+} solution with 5 μM TG ($n = 6$). Isoprenaline (Iso) values were obtained after a series of 5–10 voltage-clamp pulses to load the SR in the presence of 1 μM Iso ($n = 15$). Control values were under similar conditions but without TG or Iso present ($n = 17$). *B*, steady-state twitch $[Ca^{2+}]_i$ transients under control conditions and after exposure first to TG (to inhibit the SR Ca^{2+} pump) and then caffeine (to deplete the SR). Time constants (τ) of $[Ca^{2+}]_i$ decline are indicated. *C*, the peak of the control caffeine exposure (in 0 Na^+, 0 Ca^{2+} solution) provides an estimate of SR Ca^{2+} content (Bassani *et al.* 1994). The lower trace shows a caffeine exposure after TG application, caffeine-induced depletion and pacing at 1 Hz in an attempt to reload the SR. The lack of an observable $[Ca^{2+}]_i$ transient demonstrates effective blockade of SR Ca^{2+} uptake by TG.

(1·7 ± 0·4 s in NT *vs.* 8·9 ± 3·2 s in 0 Na^+, 0 Ca^{2+} solution), in agreement with the results of Bassani *et al.* (1994).

The second caffeine exposure after acquisition of Ca^{2+} sparks in TG caused depletion of SR Ca^{2+} content and reduced the amplitude of subsequent twitch $[Ca^{2+}]_i$ transients by ~90% (Fig. 1*B*). Figure 1*C* shows that TG completely prevented reloading of the SR as assessed by a third caffeine exposure (after TG exposure, caffeine-induced SR Ca^{2+} depletion and extensive twitches in an effort to reload). This confirms that the TG concentration used here was sufficient to completely prevent SR Ca^{2+} uptake. In addition, the τ of $[Ca^{2+}]_i$ decline during the twitch was increased by TG from 177 ± 10 to 1285 ± 215 ms, similar to previous results where SR Ca^{2+} uptake was inhibited by either TG or caffeine (Bassani *et al.* 1994). Thus, this protocol has allowed acquisition of Ca^{2+} sparks at comparable SR Ca^{2+} content in both the presence and absence of SR Ca^{2+} pump function.

Protocol to measure Ca^{2+} sparks in the presence of SR Ca^{2+} pump stimulation by isoprenaline

An additional group of cells was studied when the SR Ca^{2+} pump was stimulated by isoprenaline (1 μM). In this series, cells were voltage clamped and loaded with fluo-3 via the patch pipette. After a series of five to ten conditioning pulses (from −80 to 0 mV for 200 ms at 0·03 Hz in 0 Na^+, 2 Ca^{2+} solution) either Ca^{2+} sparks were measured or caffeine was applied (in 0 Na^+, 0 Ca^{2+} solution) to assess the SR Ca^{2+} load. This sequence was repeated after exposure to 1 μM isoprenaline for 10 min. In the presence of isoprenaline, the pulse protocol was modified so that the steady-state SR Ca^{2+} load was comparable to that for control (steps were to only −10 mV). The amplitude of caffeine-induced $[Ca^{2+}]_i$ transients in isoprenaline was not significantly different from control levels (control, 1077 ± 188 nM; isoprenaline, 1040 ± 161 nM; Fig. 1*A*).

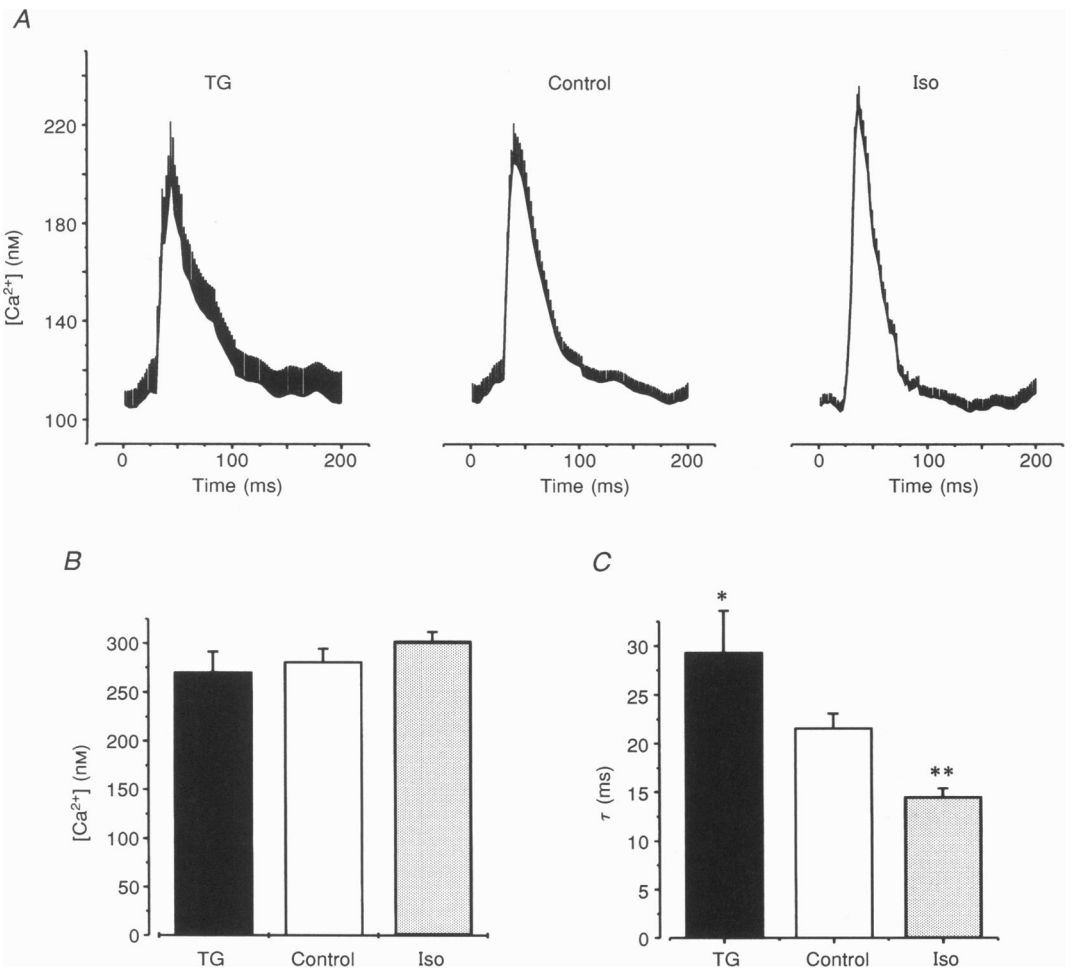


Figure 2. Ca^{2+} spark characteristics after SR Ca^{2+} pump blockade or stimulation

A, signal-averaged Ca^{2+} sparks in the 3 experimental conditions. Sparks were temporally aligned by matching their initial rising phase and the vertical lines indicate + 1 S.E.M. (n = 10, 27 and 86 Ca^{2+} sparks, respectively). *B*, mean amplitude of Ca^{2+} sparks and *C*, mean time constant of Ca^{2+} spark decline under the 3 conditions. * $P < 0.05$ and ** $P < 0.001$, significantly different from control conditions.

Ca^{2+} sparks with thapsigargin and isoprenaline

The amplitude and kinetics of control Ca^{2+} sparks were statistically indistinguishable between the control series for the TG and isoprenaline experiments above. Thus, the control sparks were pooled for further analysis. Figure 2*A* shows signal-averaged Ca^{2+} sparks for control, TG and isoprenaline experiments. Figure 2*B* shows that the amplitude of Ca^{2+} sparks was not significantly altered by either TG or isoprenaline in these experiments (control, 281 ± 13 nM; TG, 270 ± 21 nM; isoprenaline, 302 ± 10 nM; $n = 27$, 10 and 86 Ca^{2+} sparks from 8, 5 and 6 cells, respectively). This agrees with the similar SR Ca^{2+} load above and observations of a stereotypical Ca^{2+} spark amplitude (Cheng *et al.* 1993). Isoprenaline increased the frequency of Ca^{2+} sparks (from 0·63 to 1·9 s^{-1}), despite an unchanged SR Ca^{2+} load.

Figure 2*C* shows that the τ of $[Ca^{2+}]_i$ decline during Ca^{2+} sparks was different among the three groups. The τ was longest after TG (29·3 ± 4·3 ms), shortest in isoprenaline (14·5 ± 0·9 ms) and intermediate in control conditions (21·6 ± 1·5 ms). This indicates that the SR Ca^{2+}-ATPase contributes significantly to the $[Ca^{2+}]_i$ decline of the normal Ca^{2+} spark.

Spatial spread of Ca^{2+} sparks with thapsigargin and isoprenaline

The slower local $[Ca^{2+}]_i$ decline observed with SR Ca^{2+} pump blockade might also result in a greater spatial spread, since the SR Ca^{2+} pumps are expected to be broadly distributed throughout the cell. Figure 3*A* shows the time and width dependence of $[Ca^{2+}]_i$ during the averaged control Ca^{2+} spark measured in line-scan mode along the transverse axis

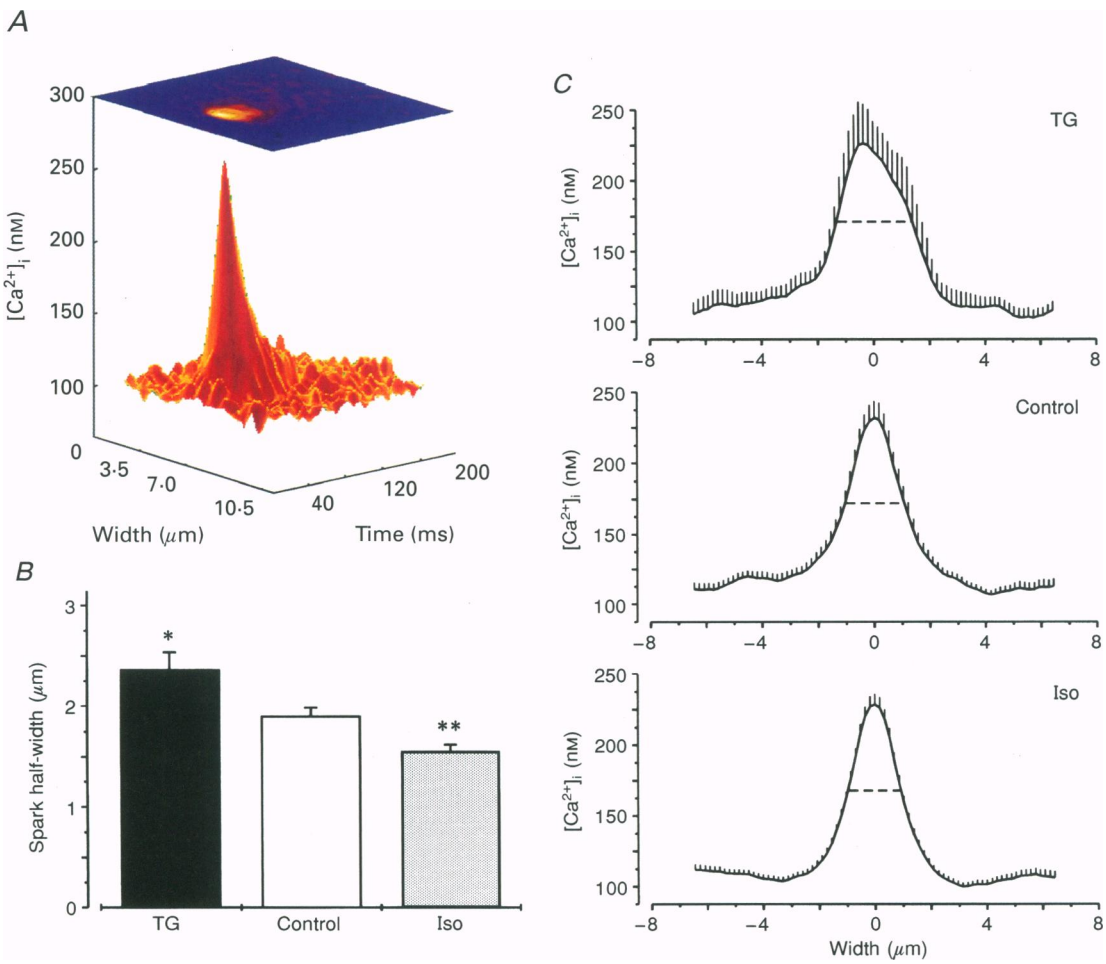


Figure 3. Spatial spread of Ca^{2+} sparks after SR Ca^{2+} pump blockade or stimulation

A, 3-D plot of local $[Ca^{2+}]_i$ during a control line scan as a function of time and distance along the transverse scan line. *B*, mean values of the Ca^{2+} spark width at half-maximal amplitude under the 3 experimental conditions. * $P < 0·05$ and ** $P < 0·01$, significantly different from control conditions. *C*, signal-averaged Ca^{2+} spark widths in the 3 experimental conditions. Sparks were aligned by placing their maximal value at $x = 0$ and the vertical lines indicate + 1 S.E.M. ($n = 10$, 27 and 86, respectively). The dashed horizontal lines indicate the full width at half-maximal amplitude.

of the cell. The Ca^{2+} spark spreads in both directions along the line being scanned without obvious asymmetry. While the precise spatial resolution along the length of the scan line is somewhat limiting, the full-width half-height of the Ca^{2+} sparks in the three conditions was significantly different (see Fig. 3*B* and *C*). The spatial spread of the Ca^{2+} sparks was largest with TG ($2{\cdot}4 \pm 0{\cdot}19$ μm), shortest in isoprenaline ($1{\cdot}56 \pm 0{\cdot}07$ μm) and intermediate in control conditions ($1{\cdot}9 \pm 0{\cdot}09$ μm). Thus the SR Ca^{2+}-ATPase function modulates both the spatial as well as temporal spread of Ca^{2+} sparks.

DISCUSSION

Ca^{2+} sparks appear to represent relatively stereotypical elementary events of SR Ca^{2+} release both during excitation–contraction coupling and at rest (Cheng *et al.* 1993; Cannell *et al.* 1994, 1995; López-López *et al.* 1995). Furthermore, the apparently homogeneous global $[Ca^{2+}]_i$ transient during a twitch probably reflects the temporal and spatial summation of many individual Ca^{2+} sparks triggered and synchronized by depolarization and consequent Ca^{2+} influx. Indeed, most of the L-type Ca^{2+} channels must be blocked so that spatially distinct Ca^{2+} sparks can be observed upon activation of the Ca^{2+} current. It is still unclear how many individual SR Ca^{2+} release channels contribute to the functional unit during an individual Ca^{2+} spark (e.g. see Cannell *et al.* 1994; Tsugorka, Rio & Blatter, 1995; Klein, Cheng, Santana, Jiang, Lederer & Schneider, 1996; Lipp & Niggli, 1996). Results in the present study also illustrate that characteristic Ca^{2+} sparks occur in the complete absence of $[Ca^{2+}]_o$ (with EGTA), indicating that Ca^{2+} influx is not essential for triggering the characteristic Ca^{2+} spark.

Since the SR Ca^{2+} content and the Ca^{2+} spark amplitude were not different, this helps to rule out potential complications due to (1) intrinsic amplitude effects on τ (Bers & Berlin, 1995), (2) slowed kinetics from Ca^{2+} sparks which originate from out of the plane of focus, or (3) fluorescence obtained from outside the nominal voxel space. Nevertheless, these sort of technical constraints place some limitations on the precise quantitative interpretation. Thus we restricted our analysis to semiquantitative terms.

As a first approximation, the rate constants (k) of $[Ca^{2+}]_i$ decline due to SR Ca^{2+}-ATPase activity and diffusion during a Ca^{2+} spark could be considered to be additive allowing some initial comparisons to be made (where $k = 1/\tau$ from data in Fig. 2*C*). Thus, the rate constant for $[Ca^{2+}]_i$ decline due to diffusion only (k_D, with TG in 0 Na^+, 0 Ca^{2+} solution) is $34{\cdot}1$ s^{-1} and that for both diffusion and the SR Ca^{2+}-ATPase activity ($k_D + k_{SR}$) is $46{\cdot}3$ s^{-1}. From these numbers it can be inferred that diffusion would account for 74% of the rate of $[Ca^{2+}]_i$ decline and SR Ca^{2+}-ATPase activity for 26%. When SR Ca^{2+}-ATPase is stimulated by isoprenaline ($k_D + k_{SR,iso} = 69{\cdot}0$ s^{-1}) this simplified analysis would indicate that the balance is changed to about 50% due to diffusion and 50% due to the stimulated SR Ca^{2+}-ATPase. This is obviously an oversimplification since the above would imply that k_{SR} is ~ 12 s^{-1}, whereas the value based on global $[Ca^{2+}]_i$ decline would give a rate constant of only about 6 s^{-1} (i.e. $\tau = 177$ ms for $[Ca^{2+}]_i$ decline during a twitch).

Another simplified quantitative consideration uses the number of Ca^{2+} ions released during a Ca^{2+} spark based on an SR Ca^{2+} release flux of 2 pA for 5 ms (31 191 Ca^{2+} ions; Tinker, Lindsey & Williams, 1993). In a 2 μm diameter sphere this would be sufficient to raise local total $[Ca^{2+}]$ by $12{\cdot}3$ μM or local mean free $[Ca^{2+}]$ by 123 nM (assuming 100 : 1 Ca^{2+} buffering; Hove-Madsen & Bers, 1993). This is comparable to the Ca^{2+} spark. The number of Ca^{2+} ions transported by SR Ca^{2+}-ATPase within this same sphere can also be calculated using the SR Ca^{2+}-pump function estimated by Bassani *et al.* (1994) in intact rat myocytes ($208\ \mu M\ s^{-1}/(1 + (184\ nM/[Ca^{2+}]_i)^{3{\cdot}9})$). The $[Ca^{2+}]_i$ which serves as the driving function (in time and space) was taken as an exponentially declining function of time (τ, 20 ms) with a Gaussian spatial profile (full width at half-maximum, 2 μm) analogous to Fig. 3*A*. Numerical integration of this Ca^{2+} pump flux yields a transport of 6616 ions or 21% of the total Ca^{2+} ions released as mentioned above. More precise mechanistic calculations would require a detailed spatiotemporal model of Ca^{2+} movements (including diffusion, buffers, pumps and leaks) beyond the scope of the present work.

We have used thapsigargin to block completely SR Ca^{2+}-ATPase during Ca^{2+} sparks. The Na^+–Ca^{2+} exchange did not contribute to $[Ca^{2+}]_i$ decline during the Ca^{2+} sparks in this study since they were measured in 0 Na^+, 0 Ca^{2+} solution. However, Na^+–Ca^{2+} exchange participation during control Ca^{2+} sparks seems unlikely because $[Ca^{2+}]_i$ decline during control Ca^{2+} sparks in 0 Na^+, 0 Ca^{2+} solution were similar to those in normal Na^+- and Ca^{2+}-containing solution (i.e. τ, $19{\cdot}6 \pm 1{\cdot}6$ s, $n = 20$, not significantly different from control 0 Na^+, 0 Ca^{2+} solution). This is not surprising since the Na^+–Ca^{2+} exchange is about ten times slower than SR Ca^{2+}-ATPase in rat ventricular myocytes (Bassani *et al.* 1992, 1994). Thus, the effect of Na^+–Ca^{2+} exchange on Ca^{2+} sparks ought to be an order of magnitude smaller than attributed here to SR Ca^{2+}-ATPase. If Ca^{2+} released during a Ca^{2+} spark has preferential access to the Na^+–Ca^{2+} exchanger rather than the SR Ca^{2+} pump, the effect could be greater.

Since the SR Ca^{2+}-ATPase and mitochondrial Ca^{2+} transport are both more than ten times slower than the Na^+–Ca^{2+} exchange (Bassani *et al.* 1992, 1994), these systems are not likely to contribute quantitatively to the decline of $[Ca^{2+}]_i$ during Ca^{2+} sparks. Slow cytosolic Ca^{2+} buffering could also contribute to the decline of $[Ca^{2+}]_i$ during Ca^{2+} sparks (e.g. at sites from which Mg^{2+} or protons might first have to dissociate before Ca^{2+} can bind), but assessment of this contribution would again require more detailed data and modelling. At higher temperature it might

be expected that the SR Ca^{2+} pump rate would increase to a greater extent than diffusion, so the SR Ca^{2+} pump would probably contribute at least as much to $[Ca^{2+}]_i$ decline during Ca^{2+} sparks at 37 °C as described here.

Isoprenaline decreases the sphere of influence of a given Ca^{2+} spark, such that SR Ca^{2+} release from one area will be less likely to induce Ca^{2+} release from a neighbouring region. In principle this aspect of SR Ca^{2+} pump stimulation would tend to decrease the propagation of Ca^{2+} waves. From a practical standpoint, however, this effect will be counterbalanced by the fact that isoprenaline stimulates SR Ca^{2+}-ATPase and load which would increase the likelihood of Ca^{2+} sparks or Ca^{2+} waves. Conversely, decreased SR Ca^{2+}-ATPase activity would increase the spread of a given Ca^{2+} spark.

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Acknowledgements

This work was supported by grants from the United States Public Health Service (HL-30077, HL-25675 and HL-36974) to D.M.B. and W.J.L. A.M.G. is supported by the Ministerio de Educación y Ciencia (EX94-03838550).

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Received 30 July 1996; accepted 14 August 1996.