

University of Massachusetts Medical School

eScholarship@UMMS

---

Open Access Articles

Open Access Publications by UMMS Authors

---

2000-05-04

## Ca(2+) entry through store-operated channels in mouse sperm is initiated by egg ZP3 and drives the acrosome reaction

Christine M. B. O'Toole

*University of Massachusetts Medical School*

*Et al.*

Let us know how access to this document benefits you.

Follow this and additional works at: <https://escholarship.umassmed.edu/oapubs>



Part of the [Cell Biology Commons](#), and the [Medicine and Health Sciences Commons](#)

---

### Repository Citation

O'Toole CM, Arnoult C, Darszon A, Steinhardt RA, Florman HM. (2000). Ca(2+) entry through store-operated channels in mouse sperm is initiated by egg ZP3 and drives the acrosome reaction. Open Access Articles. Retrieved from <https://escholarship.umassmed.edu/oapubs/1399>

This material is brought to you by eScholarship@UMMS. It has been accepted for inclusion in Open Access Articles by an authorized administrator of eScholarship@UMMS. For more information, please contact [Lisa.Palmer@umassmed.edu](mailto:Lisa.Palmer@umassmed.edu).

# Ca<sup>2+</sup> Entry through Store-operated Channels in Mouse Sperm Is Initiated by Egg ZP3 and Drives the Acrosome Reaction

Christine M.B. O'Toole,\* Christophe Arnoult,<sup>†</sup> Alberto Darszon,<sup>‡</sup>  
Richard A. Steinhardt,<sup>§</sup> and Harvey M. Florman\*<sup>||</sup>

\*Department of Cell Biology, University of Massachusetts Medical School, Worcester, Massachusetts 01655;  
<sup>†</sup>Centre d'Etudes de Grenoble, Département de Biologie Moléculaire et Structurale, 38054 Grenoble, France;  
<sup>‡</sup>Department Genética y Fisiología Molecular, Instituto d Biotecnología, Cuernavaca, Morelos 62210, México;  
and <sup>§</sup>Department of Molecular and Cell Biology, University of California, Berkeley, California 94720

Submitted December 7, 1999; Revised February 15, 2000; Accepted February 24, 2000  
Monitoring Editor: Tony Hunter

Fertilization occurs after the completion of the sperm acrosome reaction, a secretory event that is triggered during gamete adhesion. ZP3, an egg zona pellucida glycoprotein, produces a sustained increase of the internal Ca<sup>2+</sup> concentration in mouse sperm, leading to acrosome reactions. Here we show that the sustained Ca<sup>2+</sup> concentration increase is due to the persistent activation of a Ca<sup>2+</sup> influx mechanism during the late stages of ZP3 signal transduction. These cells also possess a Ca<sup>2+</sup> store depletion-activated Ca<sup>2+</sup> entry pathway that is open after treatment with thapsigargin. Thapsigargin and ZP3 activate the same Ca<sup>2+</sup> permeation mechanism, as demonstrated by fluorescence quenching experiments and by channel antagonists. These studies show that ZP3 generates a sustained Ca<sup>2+</sup> influx through a store depletion-operated pathway and that this drives the exocytotic acrosome reaction.

## INTRODUCTION

Alterations of intracellular Ca<sup>2+</sup> activity (Ca<sup>2+</sup><sub>i</sub>) mediate information transmission from many extracellular signals to internal response systems. The activation of membrane receptors can stimulate Ca<sup>2+</sup> transport through a variety of pathways, including mobilization from internal stores through inositol trisphosphate (IP3) receptor or ryanodine receptor channels or by influx through plasma membrane channels. The mechanisms that provide for spatial and temporal regulation of Ca<sup>2+</sup><sub>i</sub> are essential for the fine control of cellular function (Berridge, 1997).

This is well illustrated in sperm, in which Ca<sup>2+</sup><sub>i</sub> is an essential mediator of the acrosome reaction, a secretory event that is completed by sperm of many animal species at an early stage of fertilization (Darszon *et al.*, 1999; Florman *et al.*, 1999). In mammals, secretion is triggered during gamete contact by ZP3, a glycoprotein component of the egg's extracellular matrix, or zona pellucida (ZP). Sperm penetration of the ZP and the later events of fertilization require the prior completion of acrosome reactions (Wassarman, 1999).

Efforts to determine the mechanisms by which Ca<sup>2+</sup><sub>i</sub> is regulated by ZP3 redoubled with the recognition that inhi-

bition of Ca<sup>2+</sup><sub>i</sub> responses arrests gamete interaction in vitro (Florman *et al.*, 1989, 1992); these mechanisms may account for the reported human contraceptive effects of certain Ca<sup>2+</sup> channel antagonists (Benoff *et al.*, 1994; Hershlag *et al.*, 1995). Two phases of ZP3-evoked Ca<sup>2+</sup><sub>i</sub> responses were resolved with the use of ion-selective fluorescent probes. First, a transient Ca<sup>2+</sup><sub>i</sub> increase occurred during the first seconds of ZP3 signaling. Ca<sup>2+</sup><sub>i</sub> increased within 40–50 msec to ~10 μM and subsequently relaxed to resting values within the next 200 msec (Arnoult *et al.*, 1999). The transient response mechanism had the anticipated characteristics of a low-voltage-activated (LVA) T-type Ca<sup>2+</sup> channel, including a similar time course of activation and inhibitor sensitivity (Arnoult *et al.*, 1999). LVA Ca<sup>2+</sup> channel genes are expressed during rodent spermatogenesis (Espinosa *et al.*, 1999), and the associated currents were detected by whole cell patch clamp methods (Hagiwara and Kawa, 1984; Arnoult *et al.*, 1996a, 1997, 1998; Liévano *et al.*, 1996; Santi *et al.*, 1996). Finally, channel activation was associated with acrosome reactions (Arnoult *et al.*, 1996a). It is thus likely that transient Ca<sup>2+</sup><sub>i</sub> responses are mediated by ZP3-dependent Ca<sup>2+</sup> influx through LVA channels.

The transient response was followed by a second phase in which increased Ca<sup>2+</sup><sub>i</sub> levels were sustained for the duration of ZP3 stimulation. The sustained Ca<sup>2+</sup><sub>i</sub> response developed slowly, requiring many seconds to several minutes to reach

<sup>||</sup> Corresponding author. E-mail address: harvey.florman@umassmed.edu.

maximal levels (Florman *et al.*, 1989; Lee and Storey, 1989; Bailey and Storey, 1994; Florman, 1994; Arnoult *et al.*, 1996a,b; Shirakawa and Miyazaki, 1999), and acrosome reactions occurred after a plateau was established. The sustained response was inhibited by the addition of LVA  $\text{Ca}^{2+}$  channel antagonists before ZP3. However, both the slow activation time course of the sustained  $\text{Ca}^{2+}_i$  phase and its failure to inactivate during prolonged ZP3 stimulation were inconsistent with a direct role of LVA channels (Hille, 1992). It was instead proposed that the transient phase of  $\text{Ca}^{2+}$  entry through LVA channels was an obligatory early event leading to downstream generation of sustained  $\text{Ca}^{2+}_i$  responses through a second mechanism (Walensky and Snyder, 1995; Arnoult *et al.*, 1999).

Given the central role of  $\text{Ca}^{2+}_i$  responses in fertilization, we examined the sustained response phase in greater detail. We report that the sustained phase is mediated by  $\text{Ca}^{2+}$  entry through  $\text{Ca}^{2+}$  store depletion-activated channels. These channels are present in a wide range of cells, where they function both to refill internal  $\text{Ca}^{2+}$  stores and to participate in signal transduction processes (Berridge, 1995, 1997; Parekh and Penner, 1997). Moreover, these channels are present in mammalian sperm (Blackmore, 1993; Santi *et al.*, 1998), although their physiological role has not been determined. We have found that the store-operated  $\text{Ca}^{2+}$  channels of sperm remain functional after capacitation and play an essential role by driving the acrosome reaction during fertilization.

## MATERIALS AND METHODS

### Biological Preparations

Spermatogenic cells and sperm were obtained from CD-1 mice (12–16 wk old; Charles River Laboratories, Wilmington, MA) by manual trituration of testicular slices and from caudae epididymides, respectively. Sperm were capacitated *in vitro*, as described previously (Arnoult *et al.*, 1996a). Acrosome reactions were assessed during  $\text{Ca}^{2+}_i$  determinations with the use of differential interference contrast optics, in which acrosome-intact cells exhibit a prominent ridge in the equatorial region of the sperm head and acrosome-reacted sperm lack this ridge (Bleil and Wassarman, 1986). These results were confirmed at the end of sperm incubations with the use of a Coomassie blue staining method (Thaler and Cardullo, 1995). The fraction of motile sperm was assessed before capacitation by visual examination, and preparations with <70% motility were discarded.

Initial observations were carried out with the use of ZP extracts (40  $\mu\text{g}/\text{ml}$ ) that contained ZP3 and were confirmed with the use of purified ZP3 preparations. The responses to these two agonist preparations were indistinguishable, consistent with previous observations that ZP3 accounts for all of the agonist activity in the ZP (Bleil and Wassarman, 1983). Consequently, results obtained with these two agonist preparations are pooled for presentation.

ZPs were obtained from germinal vesicle-intact follicular oocytes and from two-cell embryos after fertilization *in vivo*. Soluble extracts were prepared by heating (60°C, 60 min). ZP2 and ZP3 were resolved by SDS-PAGE and isolated by electrophoretic elution from gel slices (Bleil and Wassarman, 1983; Arnoult *et al.*, 1996b).

### Electrophysiological Methods

$\text{Ca}^{2+}$  currents were recorded from spermatogenic cells with the use of the whole cell configuration of the patch clamp method, exactly as described (Arnoult *et al.*, 1996a). Peak LVA  $\text{Ca}^{2+}$  currents were measured during 100 msec of depolarization from holding potential

(−90 mV) to a test potential of −30 mV. Currents were recorded with the use of an Axopatch 200B amplifier (Axon Instruments, Foster City, CA). Data were sampled at 10 kHz, filtered at 3 kHz, corrected for leak and capacitance currents, and analyzed with Biopatch (Biologic, Grenoble, France).

### $\text{Ca}^{2+}_i$ Determinations

Sperm were immobilized on Cell-Tak-coated glass coverslips, transferred to a 0.1% BSA medium, and passively loaded with dye during a 15-min incubation with 1  $\mu\text{M}$  fura 2-AM and a further 15-min incubation to permit probe deesterification, exactly as described previously (Arnoult *et al.* 1996a,b). Intracellular BAPTA was loaded during similar incubations with 1  $\mu\text{M}$  BAPTA-AM (*N,N'*-[1,2-ethanediy]bis(oxy-2,1-phenylene)] bis[*N*-[2-[(acetyloxy)methoxy]-2-oxoethyl]] bis[(acetyloxy)-methyl]ester).

Extracellular dye was removed by superfusion, and coverslips were mounted on a heated microscope stage. Excitation illumination from a 75-W Xe arc lamp was directed through a 60× PlanApo objective (numerical aperture 1.3), fluorescent images were digitized with the use of a GenIVSys-intensified Dage 72 charge-coupled device camera (Dage MTI, Michigan City, IN), and data were analyzed with Axon Workbench software (Axon Instruments). Excitation wavelength pairs of 340 and 380 nm were used for  $\text{Ca}^{2+}_i$  determination, whereas 360-nm illumination was used for  $\text{Mn}^{2+}$ -quenching studies.  $\text{Ca}^{2+}_i$  values were determined with the use of the algorithm of Grynkiewicz and coworkers (1985), assuming a dissociation constant for intracellular fura 2: $\text{Ca}^{2+}$  complexes of 225 nM. Readers are cautioned that this value has not yet been confirmed specifically in sperm.

The small cytosolic volumes of sperm, and the associated low-fluorescence signals, necessitated integration of dye signals for 1–4 s in typical imaging experiments. Temporal resolution of this system, based on Nyquist's criterion (Inoue and Spring, 1997), was 2–8 s. The transient phase of the  $\text{Ca}^{2+}_i$  response, which activated and inactivated within ~250 msec (Arnoult *et al.*, 1999), is not resolved here.

### Chemicals and Reagents

AN1043 was the generous gift of Athena Neurosciences (South San Francisco, CA). Conotoxins and agatoxins were provided by Dr. Jose Lemos (University of Massachusetts). Other reagents were obtained from the following sources: nifedipine (Calbiochem, La Jolla, CA); thapsigargin, ionomycin, A-23187, fura 2-AM, BAPTA, and BAPTA-AM (Molecular Probes, Eugene, OR); Cell-Tak (Becton-Dickinson, Franklin Lakes, NJ); all other chemicals and reagents (Sigma, St. Louis, MO).

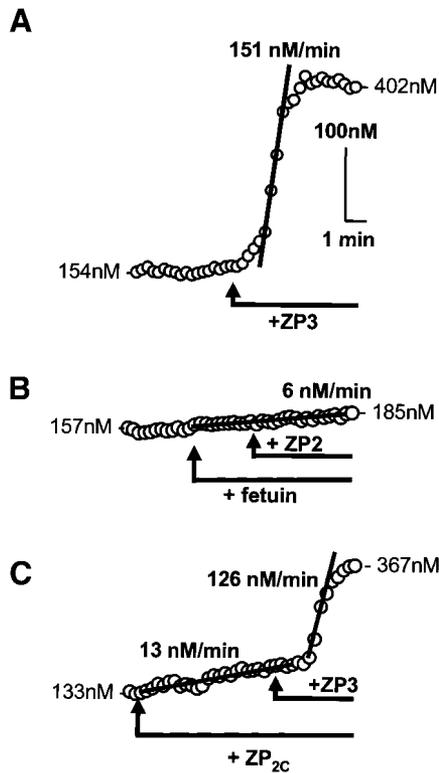
### Statistical Analysis

All data were analyzed by Student's *t* test.

## RESULTS

### ZP3 Evokes a Sustained $\text{Ca}^{2+}_i$ Increase

$\text{Ca}^{2+}_i$  in mouse sperm that were incubated under capacitating conditions was  $159 \pm 21$  nM (mean  $\pm$  SD; range, 133–193 nM; *n* = 177), as reported with fura 2. ZP3 (10  $\mu\text{g}/\text{ml}$ , ~120 nM) increased this value to  $396 \pm 24$  nM (range, 334–488 nM) in 69% (122 of 177) of the cells (Figure 1A). The remaining cells exhibited  $\text{Ca}^{2+}_i$  alterations of only  $\pm 20$  nM. The presence of a nonresponsive group is consistent with other observations that only 40–80% of mouse sperm respond to ZP3 and may reflect inefficient sperm capacitation *in vitro* (Arnoult *et al.*, 1999).



**Figure 1.** ZP3 produces a sustained  $Ca^{2+}_i$  increase in capacitated mouse sperm. (A) Resting  $Ca^{2+}_i$  values were determined before the addition of ZP3 (10  $\mu$ g/ml). Similar results were obtained with ZP extracts containing ZP3 (40  $\mu$ g/ml ZP; our unpublished results). Maximal  $Ca^{2+}_i$  response rates ( $\Delta Ca^{2+}_i/\Delta t$ ) were determined from linear fits of the slopes of time courses (straight line) and corrected for agonist-independent rates. Rate values and the initial and final calculated  $Ca^{2+}_i$  values are displayed here and in subsequent figures. (B) Control glycoproteins (10  $\mu$ g/ml fetuin and mouse ZP2) failed to initiate robust  $Ca^{2+}_i$  responses. (C) Robust  $Ca^{2+}_i$  responses were initiated by ZP3 from oocytes but not by ZP from two-cell embryos (ZP<sub>2c</sub>; 10  $\mu$ g/ml). Data are representative of 122 cells treated with ZP3 and 9–34 cells treated with control glycoproteins.

The salient characteristics of this  $Ca^{2+}_i$  response are: 1) a delay of  $1.3 \pm 0.4$  min (range, 0.5–2.8 min) before detectable  $Ca^{2+}_i$  increases; 2) an increase from 10 to 90% of peak values in  $1.9 \pm 0.4$  min (range, 0.8–3.4 min), with a maximal rate of  $176 \pm 29$  nM/min; and 3)  $Ca^{2+}_i$  values either remain increased or decline slowly ( $<10$  nM/min) in the presence of ZP3. This represents the sustained  $Ca^{2+}_i$  phase of ZP3 signaling. The earlier, transient  $Ca^{2+}_i$  response mediated by LVA channels (Arnoult *et al.*, 1999) was not resolved here.

Acrosome reactions occurred in 89% (109 of 122) of sperm exhibiting sustained  $Ca^{2+}_i$  responses and were detected at  $9.2 \pm 4.1$  min (range, 5.7–24.4 min) after addition of ZP3. A small fraction of sperm (13 of 122, 11%) generated sustained  $Ca^{2+}_i$  increases yet failed to acrosome react, as was observed previously (Arnoult *et al.*, 1996a,b). This may reflect inefficient sperm capacitation, with ZP3 signal transduction blocked at a site downstream of the sustained  $Ca^{2+}_i$  response (Yanagimachi, 1994; Florman *et al.*, 1999). In contrast, acrosome reactions were detected in only 8% (4 of 55) of

those sperm in which sustained  $Ca^{2+}_i$  increases were not detected. In control experiments, sperm were treated with 10  $\mu$ g/ml solutions of three different glycoproteins that fail to initiate acrosome reactions: fetuin, oocyte ZP2, and ZP glycoproteins from two-cell embryos (Bleil and Wassarman, 1983). These glycoproteins generated linear  $Ca^{2+}_i$  increases of  $8 \pm 5$  nM/min (Figure 1, B and C) but failed to trigger the sustained responses that were produced by oocyte ZP3. These observations, like previous studies that used antagonists of ZP3 signal transduction (Florman *et al.*, 1999), demonstrated that the sustained  $Ca^{2+}_i$  response was required for acrosome reactions.

### Role of Intracellular $Ca^{2+}$ Pools in ZP3 Signal Transduction

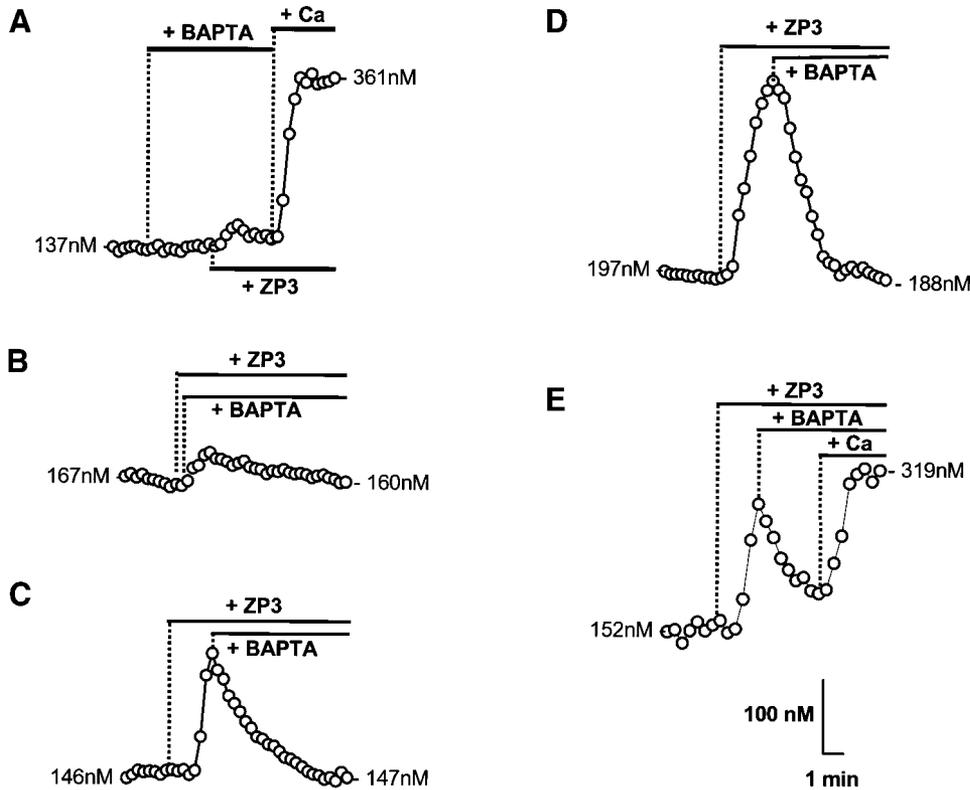
It was proposed that ZP3 promotes  $Ca^{2+}$  efflux from an intracellular pool during the initiation of acrosome reactions (Walensky and Snyder, 1995). To determine whether the mobilization of  $Ca^{2+}$  from intracellular stores was sufficient to initiate exocytosis, we examined the effects of  $Ca^{2+}$  ionophores on acrosome reactions. Ionomycin (5  $\mu$ M) increased the occurrence of acrosome reactions from  $23 \pm 5\%$  to  $52 \pm 7\%$  ( $p < 0.001$ ) during 60-min incubations in a 1.7 mM  $Ca^{2+}_o$  medium. However, when ionomycin treatments were carried out in a medium containing 5 mM extracellular BAPTA (BAPTA<sub>o</sub>; calculated  $Ca^{2+}_o < 30$  nM), acrosome reactions increased only from  $19 \pm 4\%$  in untreated populations to  $25 \pm 6\%$  ( $n = 3$ ;  $p > 0.1$ ). Similar results were obtained with a second  $Ca^{2+}$  ionophore, A23187 (our unpublished results). These agents readily release  $Ca^{2+}$  from intracellular stores, including those of sperm (Babcock *et al.*, 1976). These observations demonstrate that such  $Ca^{2+}$  release from intracellular stores is not sufficient to drive acrosome reactions.

### ZP3-activated $Ca^{2+}$ Influx Mechanisms in Sperm

These results suggest that  $Ca^{2+}$  influx may play an essential role in the generation of ZP3-dependent  $Ca^{2+}_i$  increases and acrosome reactions. This hypothesis was examined in experiments in  $Ca^{2+}_o$ -depleted medium. The reduction of  $Ca^{2+}_o$  to  $<30$  nM by BAPTA<sub>o</sub> before the addition of ZP3 inhibited the sustained  $Ca^{2+}_i$  response in 100% (18 of 18) of sperm that were examined (Figure 2A).

To determine whether  $Ca^{2+}_o$  was required specifically during the sustained response or acted indirectly by inhibiting the earlier, transient  $Ca^{2+}$  entry through LVA channels, we took advantage of the distinctive time courses of the transient and sustained responses: the sustained response occurred after a delay of  $\geq 0.5$  min, whereas the transient phase was completed within several seconds. Consequently,  $Ca^{2+}$  entry in the sustained response phase can be examined selectively by the application of  $Ca^{2+}_o$  chelators 15 s after the addition of ZP3, when the transient phase response has been completed. A similar protocol was used previously to determine the role of  $Ca^{2+}$  channels in the echinoderm acrosome reaction (Guerrero and Darszon, 1989).

When BAPTA<sub>o</sub> was added 15 s after ZP3, sustained  $Ca^{2+}_i$  increases were resolved in 13% (6 of 47) of sperm. Compared with parallel incubations in the absence of BAPTA, in which 69% of sperm exhibited a sustained  $Ca^{2+}_i$  response (Figure 1A), this represents an 81% inhibition. The remaining sperm exhibited either increases of  $<25$  nM  $Ca^{2+}_i$  (30 of 47, 64%;



**Figure 2.** Sustained  $\text{Ca}^{2+}_i$  increases after ZP3 treatment require  $\text{Ca}^{2+}_o$ . Sperm were loaded with fura 2 and incubated in a 1.7 mM  $\text{Ca}^{2+}_o$  medium. BAPTA and  $\text{Ca}^{2+}_o$  (5 mM) additions served to alternate  $\text{Ca}^{2+}_o$  between  $>30$  nM and 1.7 mM, respectively. ZP3 (10  $\mu\text{g}/\text{ml}$ ) was added as indicated. Traces are representative of 13–47 cells in these treatment groups. Similar results were obtained with the use of ZP extracts.

Figure 2B) or had no detectable response (11 of 47, 23%). In a second series of experiments, sustained responses were initiated during a 2- to 3-min treatment with ZP3 before the addition of BAPTA. Chelation of  $\text{Ca}^{2+}_o$  curtailed these responses, with  $\text{Ca}^{2+}_i$  levels returning to basal values in 79% (19 of 24) of sperm that had initiated sustained responses (Figure 2, C and D). Such effects were reversible, and sustained  $\text{Ca}^{2+}_i$  responses were restored in 85% (11 of 13) of sperm after the readdition of  $\text{Ca}^{2+}_o$  in the persistent presence of ZP3 (Figure 2E). Thus, sustained  $\text{Ca}^{2+}_i$  responses required the continual presence of  $\text{Ca}^{2+}_o$ .

We then measured  $\text{Mn}^{2+}$  influx during the sustained phase of ZP3 signaling by means of fura 2 quenching (Grynkiewicz *et al.*, 1985).  $\text{Mn}^{2+}$  is conducted through many  $\text{Ca}^{2+}$  transport pathways and so provides an indirect indication of  $\text{Ca}^{2+}$  permeation (Merritt *et al.*, 1989).  $\text{Mn}^{2+}$  entry is detected with the use of the  $\text{Ca}^{2+}$ -independent emission of fura 2 (excitation wavelength, 360 nm); hence, these signals were not complicated by  $\text{Ca}^{2+}$  release from intracellular stores.

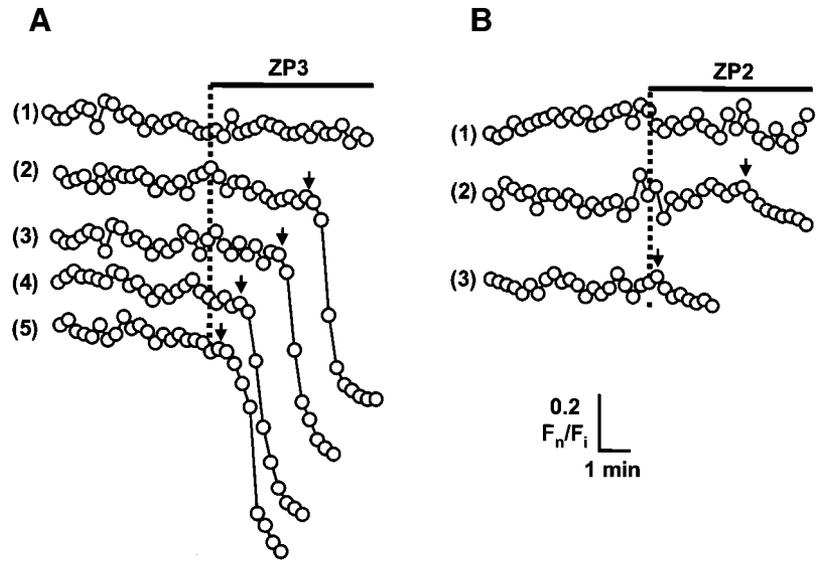
ZP3 did not alter the  $\text{Ca}^{2+}$ -independent fluorescence of fura 2 in the absence of  $\text{Mn}^{2+}_o$  (Figure 3A, upper trace), indicating that dye emission was not otherwise quenched during stimulation. However, rapid quenching occurred when  $\text{Mn}^{2+}$  was added between 0.25 and 3 min after ZP3 (Figure 3A), but not when sperm were treated with either ZP2 (Figure 3B) or fetuin (our unpublished results). These results were consistent with those of other experiments in which ZP3 failed to produce a sustained increase of  $\text{Ca}^{2+}_i$  in the presence of 100  $\mu\text{M}$   $\text{La}^{3+}$ , a nonselective  $\text{Ca}^{2+}$  entry

blocker (our unpublished results), and suggest the activation of a persistent  $\text{Ca}^{2+}$  influx mechanism.

$\text{Ni}^{2+}$  blocks LVA  $\text{Ca}^{2+}$  channels (Hille, 1992; Arnoult *et al.*, 1996a) and permitted us to determine the relationship between the persistent influx pathway and the LVA  $\text{Ca}^{2+}$  channel that was activated during the first seconds of ZP3 signaling (Arnoult *et al.*, 1999).  $\text{Ni}^{2+}$  was added to sperm either 1 min before ZP3 or 15 s after ZP3. As shown in Figure 4,  $\text{Ni}^{2+}$  inhibited the sustained  $\text{Ca}^{2+}_i$  increase with an  $\text{IC}_{50}$  of  $26 \pm 5$   $\mu\text{M}$  (○) when added before ZP3, an efficacy similar to that with which it inhibited the LVA  $\text{Ca}^{2+}$  currents of mouse spermatogenic cells, as assessed in whole cell patch clamp studies ( $\text{IC}_{50} = 34$   $\mu\text{M}$ ; Arnoult *et al.*, 1996a). In contrast, this efficacy was reduced by 18-fold when  $\text{Ni}^{2+}$  was added 15 s after ZP3 ( $\text{IC}_{50} = 481 \pm 21$   $\mu\text{M}$ ; Figure 4, ●).

Antagonists were also used to determine whether the late phase of  $\text{Ca}^{2+}$  entry was mediated by other voltage-sensitive  $\text{Ca}^{2+}$  channels. The rate of  $\text{Ca}^{2+}_i$  increase and the maximal  $\text{Ca}^{2+}_i$  value attained during the sustained response were inhibited by  $<10\%$  when blockers of N-type channels (1  $\mu\text{M}$   $\omega$ -conotoxin GVIA) or P/Q-type channels (200 nM agatoxin IVA) were added either 2 min before ZP3 or 15 s after ZP3. Inhibitors of L-type  $\text{Ca}^{2+}$  channels (1  $\mu\text{M}$  PN200-110, 50  $\mu\text{M}$  verapamil) also inhibited the sustained phase of  $\text{Ca}^{2+}$  entry by  $<10\%$  when added 15 s after ZP3. However, when these latter agents were added 2 min before ZP3, they inhibited the sustained phase of  $\text{Ca}^{2+}$  entry by  $>50\%$ . This can be attributed to their ability to block permeation through LVA T-type channels (Arnoult *et al.*, 1996a, 1998; Liévano *et al.*, 1996; Santi *et al.*, 1996). These results, together with the

**Figure 3.**  $Mn^{2+}$  influx is activated by ZP3 but not by ZP2. Sperm were loaded with fura 2 and incubated in a  $Ca^{2+}$ -depleted medium.  $Mn^{2+}$  influx was monitored by the quenching of fura 2 fluorescence (excitation wavelength, 360 nm). ZP3 or ZP2 (10  $\mu g/ml$ ) was added as indicated (bars). Times of 10  $\mu M$   $Mn^{2+}$  addition are indicated (arrows in traces A2–A5 and B2 and B3). Relative fluorescence emission data ( $F_n/F_i$ ) are presented, where  $F_n$  and  $F_i$  are emission at  $n$  min and at initial time, respectively. (A) ZP3 produces a sustained  $Mn^{2+}$  influx. Similar results were obtained with the use of ZP extracts containing ZP3 (40  $\mu g/ml$ ). (B) ZP2 does not activate a  $Mn^{2+}$  influx pathway. Traces are from 8 different cells and are typical of responses in 11 cells treated with buffer (traces A1 and B1), 37 cells treated with ZP3 or ZP solutions (traces A2–A5), and 21 cells treated with ZP2 (traces B2 and B3).



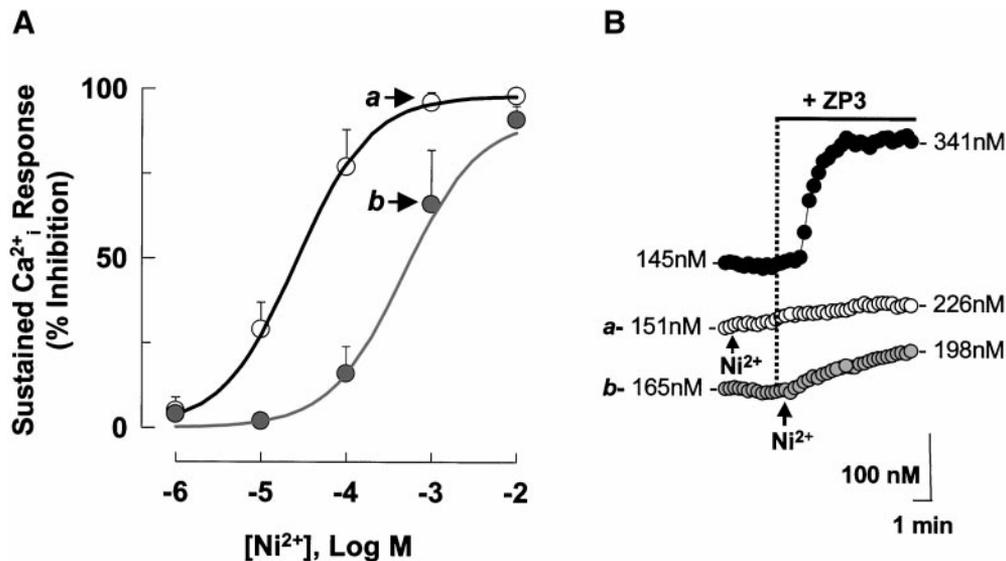
time course study results described in Figure 2, suggest that the late phase of  $Ca^{2+}$  uptake by sperm, which is required for the sustained  $Ca^{2+}_i$  response to ZP3, is through a pathway that is different from both the LVA channel and other types of voltage-sensitive  $Ca^{2+}$  channels.

#### Store-operated $Ca^{2+}$ Influx Mechanisms in Capacitated Sperm

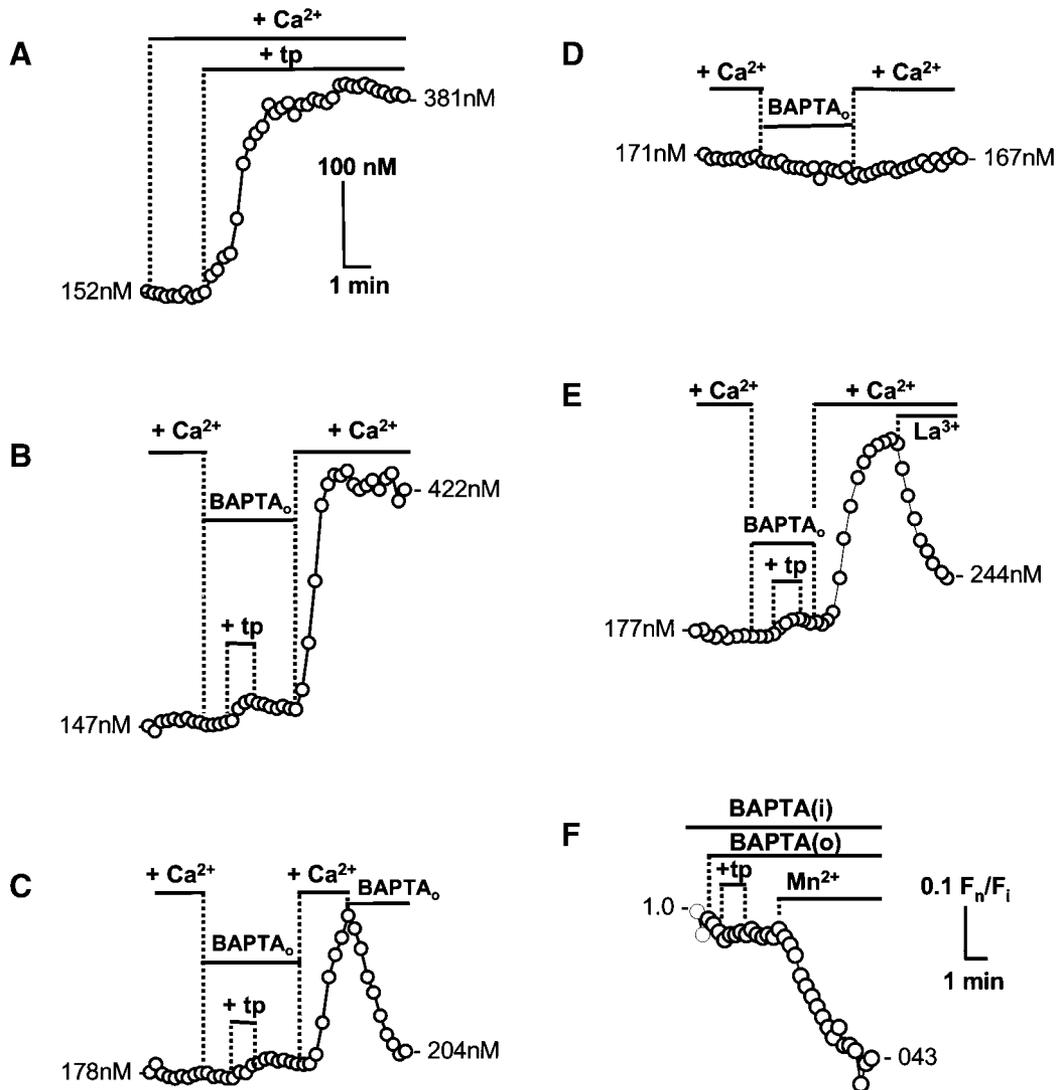
Mammalian sperm must complete a process of functional maturation, or capacitation, to fertilize eggs (Yanagimachi,

1994). A  $Ca^{2+}_i$  regulatory mechanism with the anticipated characteristics of a store-operated channel has been detected in uncapacitated sperm (Blackmore, 1993; Santi *et al.*, 1998). However, it is not known whether this permeation mechanism remains active after capacitation. A series of experiments was carried out to characterize this pathway in capacitated sperm.

$Ca^{2+}$  influx into stores is mediated by the sarcoplasmic/endoplasmic reticular  $Ca^{2+}$  ATPase, whereas efflux of sequestered  $Ca^{2+}$  occurred through  $Ca^{2+}$ -release channels or



**Figure 4.**  $Ni^{2+}$  inhibits  $Ca^{2+}_i$  responses to ZP3.  $Ni^{2+}$  was added either 2 min before (○) or 15 s after ZP3 (●). Response rates ( $\Delta Ca^{2+}_i/\Delta t$ ) were determined as described (Figure 1). (A) Data are means  $\pm$  SD of observations on 7–22 cells and are fit to the expression  $I = (100 \times IC_{50})/(IC_{50} + C)$ , where  $I$  is the inhibition of response rates in the presence  $Ni^{2+}$  and  $C$  and  $IC_{50}$  are the specific  $Ni^{2+}$  concentration and the concentration that inhibits  $Ca^{2+}_i$  response by 50%, respectively. Calculated values of  $IC_{50}$  were 26  $\mu M$  for  $Ni^{2+}$  before ZP3 (black line) and 481  $\mu M$  for  $Ni^{2+}$  after ZP3 (gray line). Letters (a and b) designate points that are illustrated by traces in B. (B) Montage of traces showing sperm treatment with 10  $\mu g/ml$  ZP3 (●), with 1 mM  $Ni^{2+}$  added 15 s after ZP3 (○), or with  $Ni^{2+}$  added 2 min before ZP3 (○).



**Figure 5.** Thapsigargin activates  $\text{Ca}^{2+}$  influx. Fura 2-loaded sperm were treated with  $10 \mu\text{M}$  thapsigargin (tp) in a  $<30 \text{ nM}$   $\text{Ca}^{2+}$  medium, and  $1.7 \text{ mM}$   $\text{Ca}^{2+}_o$  was added. (A–E) Sustained increases of  $\text{Ca}^{2+}_i$  were observed in the presence of  $\text{Ca}^{2+}_o$  and were curtailed by  $5 \text{ mM}$   $\text{BAPTA}_o$  or  $100 \mu\text{M}$   $\text{La}^{3+}$ . (F) Sperm were incubated in  $<30 \text{ nM}$   $\text{Ca}^{2+}_o$  containing  $10 \mu\text{M}$   $\text{Mn}^{2+}_o$ . Thapsigargin activated  $\text{Mn}^{2+}$  influx in fura 2/ $\text{BAPTA}_i$ -loaded sperm, resulting in quenching of fura 2 fluorescence. Fluorescence quenching data are expressed as the value  $F_i/F_o$ , as described in Figure 3. Representative traces were chosen from the following numbers of cells: (A) 71, (B) 49, (C) 44, (D) 19, (E) 17, and (F) 9.

by leak pathways. To determine whether store-operated channels were present, sperm were treated with thapsigargin, a sesquiterpene lactone that irreversibly inhibits the sarcoplasmic/endoplasmic reticulum  $\text{Ca}^{2+}$  ATPase system (Thastrup *et al.*, 1989) and results in a gradual efflux of  $\text{Ca}^{2+}$  through leak pathways (Berridge, 1995; Parekh and Penner, 1997).

Thapsigargin ( $10 \mu\text{M}$ ) produced an increase in  $\text{Ca}^{2+}_i$  of capacitated sperm incubated in a  $\text{Ca}^{2+}_o$  medium (Figure 5A). The peak  $\text{Ca}^{2+}_i$  response was  $411 \pm 36 \text{ nM}$  (range, 328–466 nM) and was detected in 87% (62 of 71) of cells observed. Responses of similar magnitude ( $396 \pm 22 \text{ nM}$ ; range, 341–455 nM) were produced by  $1 \mu\text{M}$  thapsigargin, although these occurred in a smaller fraction of cells (59%, 17

of 29 sperm) and with a highly variable delay between drug application and  $\text{Ca}^{2+}_i$  increase (1.9–7.4 min). In contrast,  $0.1 \mu\text{M}$  thapsigargin had no detectable effects on sperm  $\text{Ca}^{2+}_i$ . The efficacy of thapsigargin here ( $\text{IC}_{50} = 0.77 \mu\text{M}$ ) is lower than that typically observed in somatic cells but is similar to values reported in gametes (rat sperm,  $0.5 \mu\text{M}$  [Walensky and Snyder, 1995]; mouse eggs,  $>1 \mu\text{M}$  [Kline and Kline, 1992]).

The sustained  $\text{Ca}^{2+}_i$  increase produced by thapsigargin was dependent on  $\text{Ca}^{2+}_o$  (Figure 5B). Treatment of sperm with this drug ( $10 \mu\text{M}$ ) in a  $5 \text{ mM}$   $\text{BAPTA}_o$  medium ( $\text{Ca}^{2+}_o < 30 \text{ nM}$ ) produced only a small, transient  $\text{Ca}^{2+}_i$  increase; in 92% (45 of 49) of sperm,  $\text{Ca}^{2+}_i$  values increased by  $16 \pm 7 \text{ nM}$  and returned to basal levels in  $1.4 \pm 0.5 \text{ min}$  (ranges, 6–26

nM and 0.4–2.2 min, respectively; Figure 5, B and C). Sustained increases were not produced until 1.7 mM  $\text{Ca}^{2+}_o$  was restored (Figure 5B) and required the continued presence of  $\text{Ca}^{2+}_o$  (Figure 5C). Control experiments demonstrated that sustained  $\text{Ca}^{2+}_i$  responses were not an indirect effect of  $\text{Ca}^{2+}_o$  chelation but rather required the presence of thapsigargin (Figure 5D). To determine whether the regulation of  $\text{Ca}^{2+}_i$  by  $\text{Ca}^{2+}_o$  was due to ion influx, a series of experiments was carried out with  $\text{Ca}^{2+}$  entry antagonists. Addition of either 100  $\mu\text{M}$   $\text{La}^{3+}$  (Figure 5E) or 1 mM  $\text{Ni}^{2+}$  (our unpublished results) curtailed the sustained increase of  $\text{Ca}^{2+}_i$  that was produced by thapsigargin.

Intracellular BAPTA ( $\text{BAPTA}_i$ ) was next used to determine whether the  $\text{Ca}^{2+}$  entry that was evoked by thapsigargin depended on  $\text{Ca}^{2+}_i$  influx. Sperm were loaded with  $\text{BAPTA}_i$  and fura 2 in a  $<30$  nM  $\text{Ca}^{2+}_o$  medium (5 mM  $\text{BAPTA}_o$ ) containing 10  $\mu\text{M}$   $\text{Mn}^{2+}$  and treated with 10  $\mu\text{M}$  thapsigargin, and the activation of a cation permeation pathway was monitored by  $\text{Mn}^{2+}$ -dependent quenching of fura 2 fluorescence. Under these conditions, the small, transient increases of  $\text{Ca}^{2+}_i$  that were produced by thapsigargin (Figure 5, B, C, and E) were attenuated by  $\text{BAPTA}_i$  (our unpublished results). Nevertheless, Figure 5F shows that a cation permeation pathway was activated by thapsigargin even in the absence of detectable increases of  $\text{Ca}^{2+}_i$ . Similar responses were observed in eight of nine cells. Together, these results suggest that capacitated mouse sperm have a  $\text{Ca}^{2+}$  influx mechanism that is regulated by an intracellular  $\text{Ca}^{2+}$  store.

### Activation of Store-operated $\text{Ca}^{2+}$ Influx into Sperm by ZP3

ZP3 and thapsigargin promote increases of sperm  $\text{Ca}^{2+}_i$  that share a requirement for  $\text{Ca}^{2+}$  influx and lead to acrosome reactions. To determine if a common mechanism was activated during these two treatment protocols, we first examined whether the responses were additive.

The monitoring of  $\text{Mn}^{2+}$  influx, and the consequent quenching of fura 2 fluorescence, permitted us to detect the activation of cation entry pathways in the absence of acrosome reactions. As shown in Figure 6A, the leak rate of quenching in a 1  $\mu\text{M}$   $\text{Mn}^{2+}_o$  medium was  $0.018 \pm 0.011 [F_x/F_i] \times \text{min}^{-1}$ , and this quenching rate was increased by 4.5-fold, to  $0.082 \pm 0.023 [F_o/F_i] \times \text{min}^{-1}$  ( $p < 0.001$ ;  $n = 17$ ), by the addition of 10  $\mu\text{M}$  thapsigargin. ZP3 (10  $\mu\text{g}/\text{ml}$ ) also stimulated the quenching rate from leak levels to  $0.038 \pm 0.014 [F_o/F_i] \times \text{min}^{-1}$  ( $p < 0.002$ ). However, the sequential application of these two agents did not increase the quenching rate above that produced by thapsigargin alone (Figure 6, A and B). These results suggest that thapsigargin and ZP3 activate a similar cation permeation pathway but that thapsigargin produced a maximal stimulation and ZP3 had a submaximal effect. The alternative argument, that unknown processes limit the maximal rate of fluorescence quenching, is unlikely, because greater rates are produced by the  $\text{Mn}^{2+}$ -transporting ionophore Br-A23187 ( $0.227 \pm 0.031 [F_o/F_i] \times \text{min}^{-1}$ ;  $n = 16$ ).

This relationship was examined in greater detail by determining the effects of  $\text{Ni}^{2+}$  on the store-operated mechanism. In these experiments, sperm were treated with 10  $\mu\text{M}$  thapsigargin in a  $\text{Ca}^{2+}_o$ -depleted medium to dissipate internal  $\text{Ca}^{2+}$  stores and thereby activate store-operated  $\text{Ca}^{2+}$  influx.

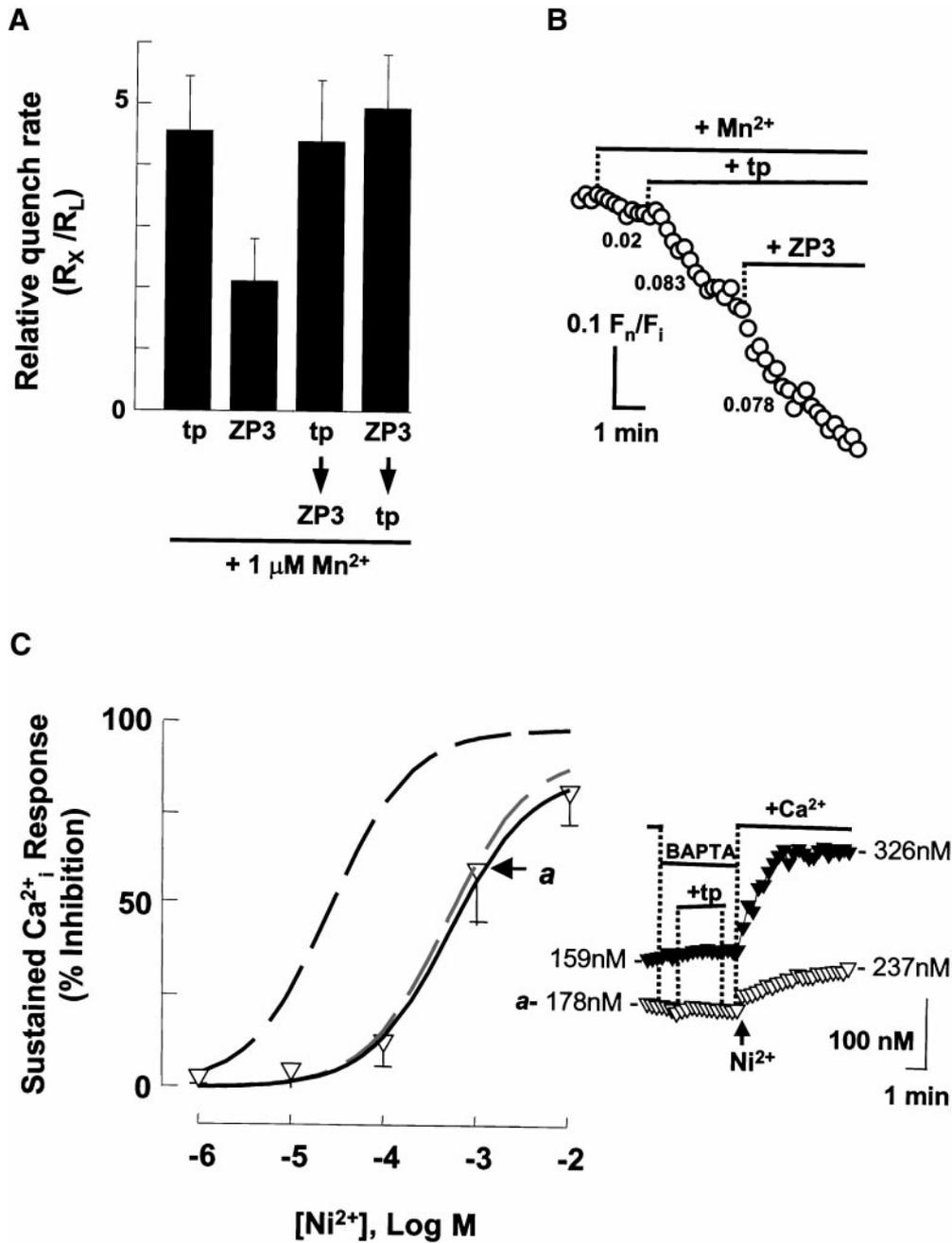
However, as shown in Figure 6C, the  $\text{Ca}^{2+}_i$  increases that occurred after the readdition of  $\text{Ca}^{2+}_o$ , and that are produced through store-operated  $\text{Ca}^{2+}$  influx in control sperm, were inhibited in a concentration-dependent manner by  $\text{Ni}^{2+}$  ( $\text{IC}_{50} = 517 \pm 19 \mu\text{M}$ ). The inhibitory efficacy is similar to that with which  $\text{Ni}^{2+}$  inhibits the persistent, ZP3-dependent  $\text{Ca}^{2+}$  influx mechanism ( $\text{IC}_{50} = 481 \pm 21 \mu\text{M}$ ; Figure 4,  $\odot$ ).

We also examined the effects of 1,4-dihydropyridines on ZP3 signal transduction and on store-operated  $\text{Ca}^{2+}$  entry. In skeletal muscle of *mdx* mice, AN1043 inhibited a  $\text{Ca}^{2+}$  entry mechanism that may be a store-operated  $\text{Ca}^{2+}$  channel but had no detectable effect on the L-type  $\text{Ca}^{2+}$  channels (Hopf *et al.*, 1996). Figure 7A shows that AN1043 is an effective inhibitor of the store-operated permeation pathway of sperm. In these experiments, the thapsigargin-activated mechanism produced an initial rate of  $\text{Ca}^{2+}_i$  increase of  $91 \pm 12$  nM/min ( $n = 31$ ) in DMSO-treated control cells; this rate was reduced by 81% to  $17 \pm 8$  nM/min ( $n = 23$ ) as a consequence of treatment with 10  $\mu\text{M}$  AN1043 ( $\text{IC}_{50} = 0.7 \pm 0.2 \mu\text{M}$ ; Figure 7B). This inhibitory action was rapid, and maximal effects were observed within 10–15 s after drug addition (our unpublished results).

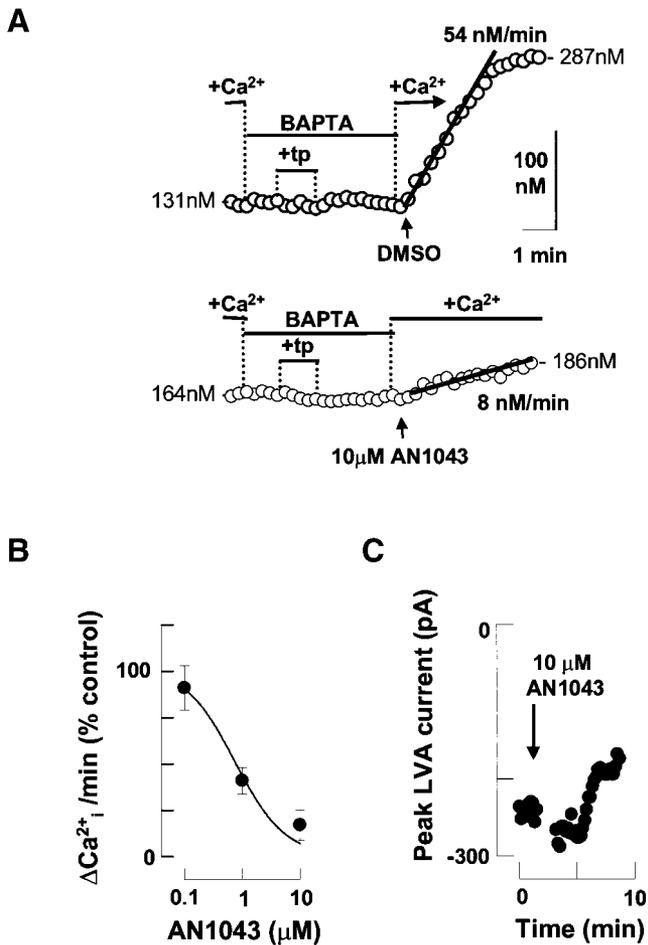
Some 1,4-dihydropyridines inhibit LVA currents (Arnoult *et al.*, 1996a, 1998; Liévano *et al.*, 1996; Santi *et al.*, 1996), and it was necessary to determine whether such an indirect effect of AN1043 might account for its inhibition of sustained  $\text{Ca}^{2+}_i$  responses in sperm. Therefore, we examined the effects of 10  $\mu\text{M}$  AN1043 on the LVA  $\text{Ca}^{2+}$  currents of spermatogenic cells with the use of the whole cell patch clamp method. A slow, partial inhibition was observed in which LVA currents were inhibited by  $<20\%$ , and 5 min was required for maximal inhibition (Figure 7C).

AN1043 treatment, therefore, was initiated either 5 min before the addition of ZP3, when it is expected to inhibit both the transient and the sustained  $\text{Ca}^{2+}_i$  regulators, or 15 s after ZP3 addition, in which case it would selectively block the sustained mechanism. Figure 8A shows that acrosome reactions were inhibited by  $>80\%$  when sperm were treated with AN1043 for 5 min before the addition of ZP3. Similar effects were observed with nifedipine, a related 1,4-dihydropyridine that inhibited spermatogenic cell LVA  $\text{Ca}^{2+}$  channels (Arnoult *et al.*, 1996a, 1998) but had no effect on the putative store-operated pathway of *mdx* mice (Hopf *et al.*, 1996). In contrast, when drugs were added 15 s after ZP3, AN1043 produced a concentration-dependent inhibition of the acrosome reaction ( $\text{IC}_{50} = 1.1 \pm 0.2 \mu\text{M}$ ; Figure 8, A and B), whereas nifedipine had no effect. It is unlikely that AN1043 was acting indirectly at a site downstream of the  $\text{Ca}^{2+}_i$  response, because acrosome reactions are triggered in AN1043-treated sperm by 5  $\mu\text{M}$  ionomycin, the  $\text{Ca}^{2+}$  ionophore (our unpublished results).

AN1043, when added 15 s after ZP3, also reduced the sustained increase of  $\text{Ca}^{2+}_i$  in a concentration-dependent manner ( $\text{IC}_{50} = 0.8 \pm 0.1 \mu\text{M}$ ; Figure 8C). A series of fluorescence quenching experiments was carried out with 1  $\mu\text{M}$   $\text{Mn}^{2+}_o$  to determine whether the mechanism of dihydropyridine action was through an inhibition of cation influx. The thapsigargin-evoked rate of fluorescence quenching was reduced by 45%, from  $0.092 \pm 0.020 [F_o/F_i] \times \text{min}^{-1}$  to  $0.051 \pm 0.017 [F_o/F_i] \times \text{min}^{-1}$ , by 1  $\mu\text{M}$  AN1043 ( $n = 9$ ); it was further reduced by 73%, to  $0.025 \pm 0.009 [F_o/F_i] \times$



**Figure 6.** Thapsigargin and ZP3 activate a similar cation permeation pathway in sperm. Fura 2-loaded sperm were incubated in a  $<30$  nM  $Ca^{2+}_o$  medium, and  $Ca^{2+}$ -independent dye fluorescence was monitored as described in Figure 3.  $Mn^{2+}$  ( $1 \mu M$ ), thapsigargin (tp;  $10 \mu M$ ) and ZP3 ( $10 \mu g/ml$ ) were added (dashed lines), and fluorescence quenching rates were determined by the slopes of these traces. (A) Quenching rates ( $[F_x/F_i]/[t_x/t_i]$ , where  $F_x$  and  $F_i$  are the fluorescence emission at  $x$  min [ $t_x$ ] and at the initial time [ $t_i$ ], respectively) were determined for individual sperm during a 2-min incubation in  $1 \mu M Mn^{2+}$  and designated  $R_L$  (leak rate). Quenching rates during experimental treatment ( $R_x$ ) were determined during a 10-min incubation with thapsigargin or with ZP3 or by the addition of one reagent followed 3 min later by the second reagent. Results are expressed as the relative quench rate ( $R_x/R_L$ ) and are the mean of observations on 12–39 sperm. (B) A fluorescence trace showing the effects of thapsigargin and ZP3 on  $Mn^{2+}$ -dependent quenching. Data from this and other cells were used to construct panel A. (C)  $Ni^{2+}_o$  inhibits thapsigargin-induced  $Ca^{2+}_i$  responses. Thapsigargin triggered  $Ca^{2+}_i$  increases upon addition of  $Ca^{2+}_o$ . Addition of  $Ni^{2+}$  15 s after  $Ca^{2+}_o$  inhibited this response in a concentration-dependent manner ( $\nabla$ ). Data were fit to the expression described in Figure 4, and the derived  $IC_{50}$  value was  $517 \mu M$ . For comparison, fit curves for the inhibition of the early (black dashed line) and late (gray dashed line) phases of ZP3-evoked  $Ca^{2+}_i$  responses are redrawn from Figure 4A. The letter (a) designates the point that is used in the traces to the right. These traces are from two sperm in which thapsigargin triggered  $Ca^{2+}_i$  responses in the absence ( $\blacktriangledown$ ) and in the presence ( $\nabla$ ) of  $1 \mu M Ni^{2+}_o$ .



**Figure 7.** AN1043 inhibits the thapsigargin-dependent Ca<sup>2+</sup><sub>i</sub> regulator of sperm but not the LVA channel. (A) The Ca<sup>2+</sup> permeation pathway of sperm was activated by treatment with 10 μM thapsigargin (tp), followed by the addition of 1.7 mM Ca<sup>2+</sup><sub>o</sub>. AN1043 (10 μM) or DMSO was added 15 s after Ca<sup>2+</sup><sub>o</sub>. Initial and final Ca<sup>2+</sup><sub>i</sub> values are displayed, as are the maximum response rates. Traces are representative of observations on 31 cells treated with control medium and 23 cells treated with AN1043. (B) Dose-response relationship for the inhibition of sustained Ca<sup>2+</sup><sub>i</sub> by AN1043. Data points are means (±SD) of observations on 16–23 cells in AN1043 treatment groups and were normalized to a population of 31 cells that were treated with thapsigargin in the absence of AN1043. Data are fit to the same expression as in Figure 4, where the derived IC<sub>50</sub> value was 0.7 ± 0.2 μM. (C) Effects of AN1043 on the LVA current of mouse pachytene spermatocyte. Peak whole cell Ca<sup>2+</sup> currents were recorded after test depolarizations to -30 mV from a holding potential of -90 mV. AN1043 (10 μM) was added as indicated. AN1043 reduced the peak current by 20% from an initial value of 245 pA. Data are representative of current recordings on six cells.

min<sup>-1</sup>, by 10 μM AN1043 (n = 7). Similarly, the ZP3-triggered quenching rate was reduced by 56%, from 1.03 ± 0.018 [F<sub>o</sub>/F<sub>i</sub>] × min<sup>-1</sup> to 0.046 ± 0.021 [F<sub>o</sub>/F<sub>i</sub>] × min<sup>-1</sup>, by 1 μM AN1043 (n = 6); it was further reduced by 81%, to 0.020 ± 0.011 [F<sub>o</sub>/F<sub>i</sub>] × min<sup>-1</sup>, by 10 μM AN1043 (n = 13). The derived IC<sub>50</sub> values for inhibition of thapsigargin- and ZP3-dependent fluorescence quenching were 0.9 ± 0.2 μM and 0.9 ± 0.3 μM, respectively.

We also examined the effects of two LVA current antagonists (10 μM nifedipine and 10 μM fluspirilene; Arnoult *et al.*, 1998), which had no effect on the thapsigargin-activated Ca<sup>2+</sup> entry pathway. These agents inhibited the sustained response by <10% when added to sperm 15 s after ZP3 (our unpublished results).

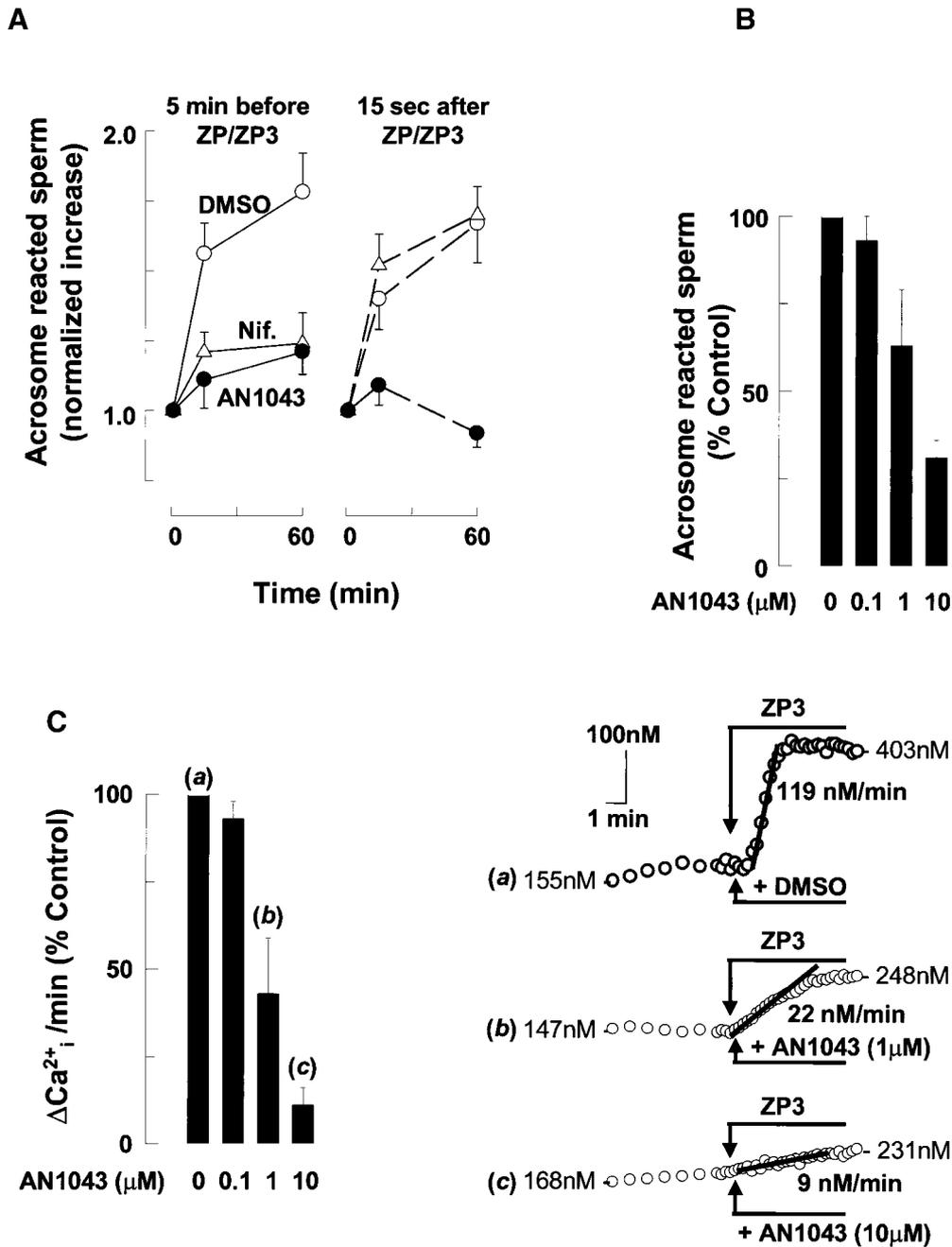
## DISCUSSION

The central conclusions of this study are that egg ZP3 activates a late stage of Ca<sup>2+</sup> influx into mouse sperm, that this influx is due to the opening of a Ca<sup>2+</sup> store depletion-activated Ca<sup>2+</sup> entry mechanism, and that the Ca<sup>2+</sup> entering through this pathway controls the progress of acrosome reactions. A late phase of Ca<sup>2+</sup> influx during ZP3 signal transduction was identified based on observations that the sustained ionic response required Ca<sup>2+</sup><sub>o</sub> was attenuated by late addition of Ca<sup>2+</sup> entry antagonists, and was associated with Mn<sup>2+</sup> influx.

The permeation pathway mediating Ca<sup>2+</sup> entry during the sustained phase is distinct from the LVA Ca<sup>2+</sup> channel that is activated during the first seconds of ZP3 signaling. LVA Ca<sup>2+</sup> channels have been characterized in spermatogenic cells by patch clamp techniques (Hagiwara and Kawa, 1984; Arnoult *et al.*, 1996a; Liévano *et al.*, 1996; Santi *et al.*, 1996) and in sperm with the use of optical methods (Arnoult *et al.*, 1999). The LVA Ca<sup>2+</sup> channel was inhibited by Ni<sup>2+</sup> and nifedipine (IC<sub>50</sub> = 34 and 0.4 μM, respectively; Arnoult *et al.*, 1996a, 1998) but was only partially blocked by 10 μM AN1043, whereas the late phase of influx was less sensitive to inhibition by Ni<sup>2+</sup> (IC<sub>50</sub> = 481 μM; Figure 4) and nifedipine (<10% inhibition by 10 μM nifedipine) but was more sensitive to inhibition by AN1043 (IC<sub>50</sub> = 0.8 μM; Figure 8). Thus, a second Ca<sup>2+</sup> influx mechanism was activated during the later phases of ZP3 signaling and mediated the sustained Ca<sup>2+</sup><sub>i</sub> response.

A question arises concerning the relationship between the activation of LVA Ca<sup>2+</sup> currents and of the late phase of Ca<sup>2+</sup> entry. LVA Ca<sup>2+</sup> channel antagonists, when applied before ZP3, inhibited both pathways with efficacies that were similar to those with which they inhibited LVA Ca<sup>2+</sup> currents in spermatogenic cells (Arnoult *et al.*, 1996a; present study). In contrast, when antagonists were added after ZP3-induced LVA Ca<sup>2+</sup> currents had inactivated, they either failed to block sustained Ca<sup>2+</sup><sub>i</sub> responses (>10% inhibition with nifedipine and fluspirilene) or did so with efficacies that did not reflect action on LVA currents (Ni<sup>2+</sup>). Thus, early activation of LVA Ca<sup>2+</sup> channels was required for the later, sustained phase of Ca<sup>2+</sup> entry. The precise role of transient Ca<sup>2+</sup> entry in the generation of sustained Ca<sup>2+</sup><sub>i</sub> responses is poorly understood. Yet, simple models in which Ca<sup>2+</sup> entry during the transient phase is required to open the sustained channel can be rejected, because fura 2-quenching experiments demonstrated the opening of that latter channel even in the absence of Ca<sup>2+</sup><sub>o</sub> (Figure 3). More complex models can be envisioned.

A second question concerns the identification of the sustained Ca<sup>2+</sup> influx pathway. Several lines of evidence suggest that influx occurs through the Ca<sup>2+</sup> store-operated channel. Ca<sup>2+</sup> channels that are activated by depletion of intracellular Ca<sup>2+</sup> stores have been well characterized in nonexcitable cells (Parekh and Penner, 1997) and may also



**Figure 8.** AN1043 inhibits ZP3 signal transduction. (A) Sperm were treated with 10 μM AN1043 (●), 10 μM nifedipine (△), or DMSO vehicle (○) added either 5 min before (left) or 15 s after (right) the addition of 10 μg/ml ZP3 or 40 μg/ml ZP extracts. Acrosome reactions were determined during a 60-min incubation, and data were normalized according to the expression  $AR = (AR_i - AR_0)/(AR_0)$ , where  $AR_0$  and  $AR_i$  are the acrosome reaction levels before ZP/ZP3 addition and at  $i$  min.  $AR_0$  was  $21 \pm 8$  and  $17 \pm 5\%$  when drugs were added before or after agonists, respectively. (B) Dose-response relationship for the inhibition of acrosome reactions after the addition of AN1043 15 s after ZP/ZP3. Acrosome reactions were determined 30 min after the addition of ZP/ZP3. Results are normalized according to the expression  $AR = 100 \times [(AR_{AN30} - AR_0)/(AR_{30B} - AR_0)]$ , where  $AR_0$ ,  $AR_{AN30}$ , and  $AR_{30B}$  are the levels of acrosome reactions at 0 min, at 30 min in the presence of AN1043, and at 30 min in the absence of AN1043, respectively. The derived  $IC_{50}$  for inhibition of the acrosome reaction was  $1.1 \pm 0.2$  μM. Data in A and B represent the means ( $\pm$ SD) of triplicate experiments, with 200 sperm examined at each time or concentration point in each experiment. (C) AN1043 inhibits the sustained  $Ca^{2+}_i$  response that is activated by ZP/ZP3.  $Ca^{2+}_i$  was monitored after the addition of either 10 μg/ml ZP3 or 40 μg/ml ZP. AN1043 or DMSO was added 15 s after the agonist. Response rates ( $\Delta Ca^{2+}_i/\Delta t$ ) were determined as described in Figure 1. (Left) Pooled response (means  $\pm$  SD) of observations on 12–47 cells. Data were normalized according to the same expression as in B, in which data reflect rates ( $\Delta Ca^{2+}_i/\Delta t$ ) rather than acrosome reaction values. The derived  $IC_{50}$  value for inhibition of the  $Ca^{2+}_i$  response was  $0.8 \pm 0.1$  μM. Letters above the bars refer to individual traces shown on the right. (Right) Representative traces for sperm treated with 0 μM (a), 1 μM (b), or 10 μM (c) AN1043.

operate in excitable cells (Zhu *et al.*, 1996; Garcia and Schilling, 1997; Philipp *et al.*, 1998; Fomina and Nowycky, 1999; Li *et al.*, 1999; Liman *et al.*, 1999). The presence of a store-operated  $\text{Ca}^{2+}$  entry mechanism in sperm was suggested from studies of uncapacitated human sperm (Blackmore, 1993) and spermatogenic cells and testicular sperm of mouse (Santi *et al.*, 1998). Because mammalian sperm require capacitation to express fertilizing ability (Yanagimachi, 1994), and because capacitation may include alterations in  $\text{Ca}^{2+}$  metabolism (Fraser *et al.*, 1995), it was necessary to determine whether this mechanism also operated in capacitated sperm. We observed that thapsigargin activated a  $\text{Ca}^{2+}$  influx mechanism in capacitated sperm populations that was dependent on  $\text{Ca}^{2+}_o$ , was blocked by  $\text{Ca}^{2+}$  entry inhibitors, and was associated with cation influx. The thapsigargin-induced release of  $\text{Ca}^{2+}$  from internal stores could promote  $\text{Ca}^{2+}$  influx either through a store depletion-activated channel or through a  $\text{Ca}^{2+}_i$ -activated cation channel (Parekh and Penner, 1997). However, the role of a  $\text{Ca}^{2+}_i$ -gated channel in ZP3 signaling is unlikely, because the sustained entry mechanism into sperm was activated by thapsigargin even when internal chelators prevented increases of  $\text{Ca}^{2+}_i$  (Figure 5F). Thus, thapsigargin activated a  $\text{Ca}^{2+}$  influx pathway into capacitated sperm with the anticipated characteristics of a  $\text{Ca}^{2+}$  store depletion-activated channel.

The thapsigargin-evoked permeation pathway shares several features with the pathway that mediates the late phase of ZP3-dependent  $\text{Ca}^{2+}$  entry. Both pathways were insensitive to nifedipine and fluspirilene but were inhibited by  $\text{Ni}^{2+}$  and AN1043. These latter two reagents cannot be considered highly selective, yet they inhibited both the  $\text{Ca}^{2+}$  entry mechanism that is promoted by thapsigargin and that activated during the late phase of ZP3 signaling with similar efficacies: the  $\text{IC}_{50}$  values were, respectively,  $517 \pm 29 \mu\text{M}$  and  $481 \pm 22 \mu\text{M}$  for  $\text{Ni}^{2+}$  and  $0.7 \pm 0.2 \mu\text{M}$  and  $0.8 \pm 0.1 \mu\text{M}$  for AN1043. Moreover, as noted previously, these reagents have markedly different effects on the sperm LVA  $\text{Ca}^{2+}$  current. Thus,  $\text{Ca}^{2+}$  entry pathways in sperm can be differentiated with  $\text{Ni}^{2+}$  and AN1043. Finally, the cation influx rate evoked by a maximal dose of thapsigargin was not enhanced by the subsequent addition of ZP3 (Figure 6). This lack of synergy suggests that these agents work through a common mechanism. Interestingly, when the sequence of treatment was reversed, thapsigargin enhanced the influx rate above the ZP3-evoked rate and the final rate never again exceeded that produced by thapsigargin alone. It is interesting to speculate that this finding reflects a more localized action of ZP3. These observations strongly suggest that ZP3 promoted a late phase of  $\text{Ca}^{2+}$  entry through a store depletion-activated channel.

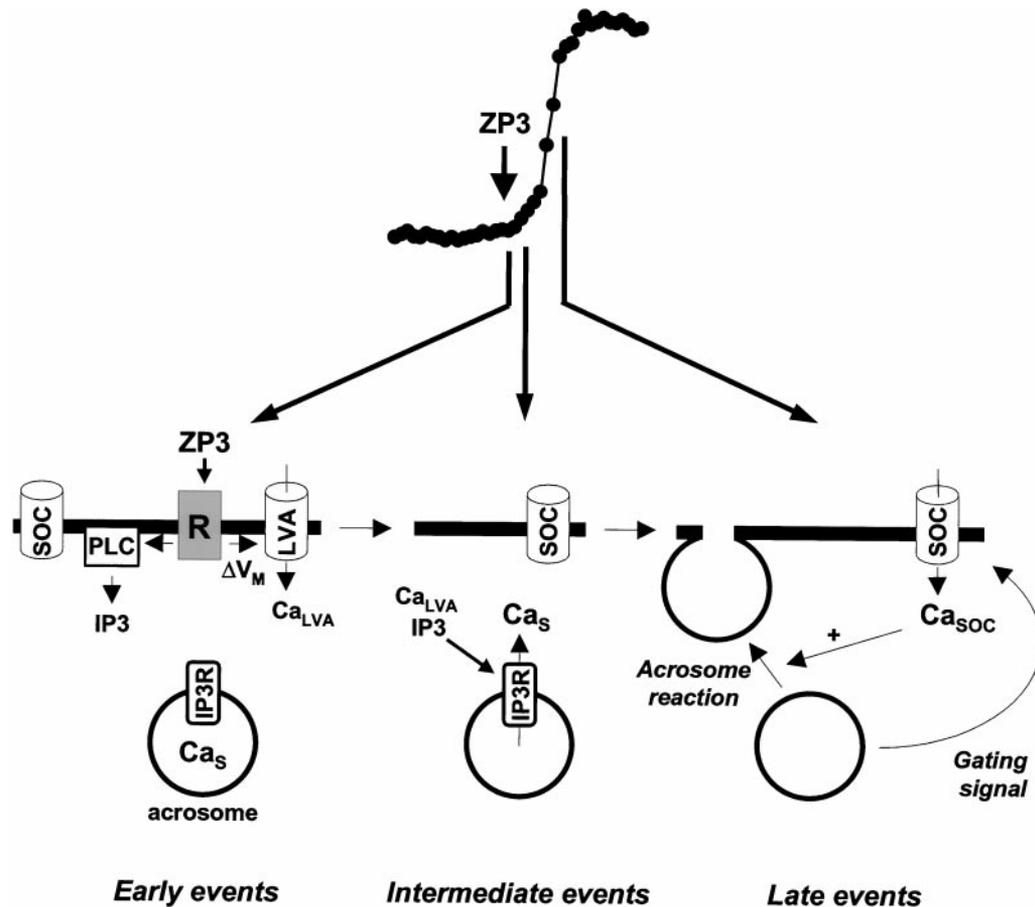
In this regard, the presence of internal  $\text{Ca}^{2+}$  stores in sperm has been questioned, based on the absence of endoplasmic reticulum. However, acrosomal membranes contain both a  $\text{Ca}^{2+}$ -ATPase (Gordon, 1973; Gordon *et al.*, 1978) and IP3 receptors (Walensky and Snyder, 1995; Zapata *et al.*, 1997; Trevino *et al.*, 1998). Moreover, a thapsigargin-sensitive  $\text{Ca}^{2+}$  pump was identified in bovine sperm membranes and tentatively localized to the acrosome (Spungin and Breitbart, 1996). It is likely, therefore, that the acrosome functions as an internal store of releasable  $\text{Ca}^{2+}$ , as was first suggested by Walensky and Snyder (1995), and as the target for thapsigargin action. Similarly, secretory granules may

serve as pools of mobilizable  $\text{Ca}^{2+}$  in somatic cells (Petersen, 1996).

Store-operated  $\text{Ca}^{2+}$  channels were initially presumed to function chiefly to facilitate refilling of intracellular  $\text{Ca}^{2+}$  stores (Putney, 1977), but they are now understood to participate in signal transduction. In some cells, influx through this pathway maintains  $\text{Ca}^{2+}$  levels in intracellular stores that may otherwise be depleted during production of repetitive  $\text{Ca}^{2+}_i$  spikes (Putney, 1986; Takemura and Putney, 1989). More recently, it was suggested that these channels can generate  $\text{Ca}^{2+}$  signals directly. For example, store-operated  $\text{Ca}^{2+}$  influx is an essential signal for T lymphocyte activation by antigen (Zweifach and Lewis 1993; Fanger *et al.*, 1995) and may also permit regulation of signal-transducing elements (Parekh and Penner, 1997; Fagan *et al.*, 1998).

A model for the control of sperm  $\text{Ca}^{2+}_i$  during fertilization can be proposed based on these and other results (Figure 9). The early events of ZP3 signal transduction may consist of the generation of two second messengers: 1) LVA  $\text{Ca}^{2+}$  channels activate during the first seconds of ZP3 signaling, likely in response to a more rapid membrane depolarization (Florman, 1994), and generate a transient  $\text{Ca}^{2+}$  influx (Arnoult *et al.*, 1999); and 2) phospholipase C is activated, leading to the production of IP3 (Roldan *et al.*, 1994; Tomes *et al.*, 1996). An intermediate stage of ZP3 signaling consisted of activation of the IP3 receptor, leading to depletion of intracellular  $\text{Ca}^{2+}$  stores. Given the facts that ZP3 stimulated IP3 production in sperm, that IP3 receptors were present in acrosomal membranes (Walensky and Snyder, 1995; Zapata *et al.*, 1997; Trevino *et al.*, 1998), and that IP3 evoked  $\text{Ca}^{2+}$  release from intracellular stores of digitonin-permeabilized sperm (Walensky and Snyder, 1995), it is likely that such  $\text{Ca}^{2+}$  pool mobilization is an element of ZP3 signal transduction. Mobilization of stored  $\text{Ca}^{2+}$  has not been detected directly, possibly because of the small size of mouse acrosomes and a limited understanding of sperm  $\text{Ca}^{2+}_i$  buffering. It is tempting to speculate that transient  $\text{Ca}^{2+}_i$  increases induced by ZP3 or thapsigargin in the absence of  $\text{Ca}^{2+}_o$  (Figures 2A and 5, B and C) represent pool emptying. In any case,  $\text{Ca}^{2+}_o$  was required for the production of sustained  $\text{Ca}^{2+}_i$  responses (Figure 2) and acrosome reactions by ZP3 and for either the production of  $\text{Ca}^{2+}_i$  responses or secretion by  $\text{Ca}^{2+}$  ionophores or thapsigargin (Blackmore, 1993; Meizel and Turner, 1993; Spungin and Breitbart, 1996; present study). These observations strongly suggest that  $\text{Ca}^{2+}$  release from intracellular stores is not sufficient to drive acrosome reactions.

The final stage of ZP3 signal transduction consists of the generation of gating signals that couple store depletion to the opening of store-operated permeation pathways in the plasma membrane. This gating signal is not well characterized and may entail generation of soluble messengers, a mechanical coupling mechanism, or a secretion-based mechanism (Berridge, 1995; Parekh and Penner, 1997; Patterson *et al.*, 1999; Yao *et al.*, 1999). Other ZP3-dependent processes may further modulate  $\text{Ca}^{2+}$  conductance through this pathway. For example, ZP3 produced transient increases of sperm internal pH that develop with the same time course as sustained  $\text{Ca}^{2+}_i$  responses (Arnoult *et al.*, 1996b), and the store-operated  $\text{Ca}^{2+}$  channel of mouse spermatogenic cells is controlled by internal pH (Santi *et al.*, 1998). In any case, the



**Figure 9.** Model of the ionic events of ZP3 signal transduction. (Top) ZP3 increases sperm  $\text{Ca}^{2+}_i$ . (Bottom) This response may be due to the sequential activation of three  $\text{Ca}^{2+}$  channels. (Early events) ZP3 activation of a receptor (R) results in: 1) membrane depolarization ( $\Delta V_M$ ) and the subsequent  $\text{Ca}^{2+}$  influx ( $\text{Ca}_{LVA}$ ) through LVA  $\text{Ca}^{2+}$  channels; and 2) the activation of phospholipase C (PLC), leading to the generation of IP3. (Intermediate events) IP3 activates IP3 receptors (IP3R) in the acrosomal membrane, leading to an efflux of  $\text{Ca}^{2+}$  from this internal store ( $\text{Ca}_s$ ) into the cytosol. (Late events) Depletion of intracellular  $\text{Ca}^{2+}$  stores produces a signal (gating signal) that opens a store-operated  $\text{Ca}^{2+}$  channel (SOC) in the plasma membrane. SOC activation also requires  $\text{Ca}_{LVA}$  and may be further regulated by other ZP3-dependent events, such as increased internal pH. The resultant  $\text{Ca}^{2+}$  influx ( $\text{Ca}_{SOC}$ ) drives acrosome reactions.

$\text{Ca}^{2+}$  that acts as a signal for secretion then enters and drives the final stages of the acrosome reaction.

The protracted time course of the sustained  $\text{Ca}^{2+}_i$  response and acrosome reaction may reflect the sustained activation of store-operated  $\text{Ca}^{2+}$  entry. It is interesting to speculate that the acrosome reaction requires sustained  $\text{Ca}^{2+}$  influx, such as is provided by store-operated channels, to prevent precocious activation and loss of sperm function in cells with a single secretory granule. A similar need may underlie the use of store-operated channels to drive gene expression during T cell activation (Crabtree, 1999). In contrast, the delay before the generation of sustained  $\text{Ca}^{2+}_i$  responses, which is  $>30$  s in mouse and bovine sperm (Florman *et al.*, 1989; Lee and Storey, 1989; Bailey and Storey, 1994; Arnoult *et al.*, 1996a) but may be only several seconds in hamster sperm (Shirakawa and Miyazaki, 1999), may provide a measure of the rates of upstream processes such as  $\text{Ca}^{2+}$  store depletion.

One benefit of this model is that it may account for the reported presence of additional acrosome reaction-inducing

agonists. For example, progesterone, which also promotes secretion, activates phospholipase C (Thomas and Meizel, 1989) and may thus deplete sperm  $\text{Ca}^{2+}$  stores and activate the same store-operated channel. The convergence of these pathways is consistent with reports that progesterone and ZP3 activate distinct upstream signaling elements (Tesarik *et al.*, 1993; Murase and Roldan, 1996) and yet act cooperatively in driving secretion (Roldan *et al.*, 1994). More generally, agents that deplete internal  $\text{Ca}^{2+}$  stores are expected to act in a synergistic manner with ZP3, whereas agents that inhibit such depletion or otherwise prevent  $\text{Ca}^{2+}$  entry through store-operated pathways may act as noncompetitive antagonists of ZP3-dependent acrosome reactions and of fertilization.

#### ACKNOWLEDGMENTS

This work was supported by the National Institutes of Health (grants HD 32177 and GM 56479 to H.M.F. and grant AR 44066 to R.A.S.); by the Centre National de la Recherche Scientifique (C.A.);

and by Consejo Nacional de Ciencia y Tecnología, Dirección General de Asuntas para el Personal Académico, Howard Hughes Medical Institute, and the International Center for Genetic Engineering and Biotechnology (A.D.).

## REFERENCES

- Arnoult, C., Cardullo, R.A., Lemos, J.R., and Florman, H.M. (1996a). Activation of mouse sperm T-type  $\text{Ca}^{2+}$  channels by adhesion to the egg zona pellucida. *Proc. Natl. Acad. Sci. USA* *93*, 13004–13009.
- Arnoult, C., Kazam, I.G., Visconti, P.E., Kopf, G.S., Villaz, M., and Florman, H.M. (1999). Control of the low voltage-activated calcium channel of mouse sperm by egg ZP3 and by membrane hyperpolarization during capacitation. *Proc. Natl. Acad. Sci. USA* *96*, 6757–6762.
- Arnoult, C., Lemos, J.R., and Florman, H.M. (1997). Voltage-dependent modulation of T-type  $\text{Ca}^{2+}$  channels by protein tyrosine phosphorylation. *EMBO J.* *16*, 1593–1599.
- Arnoult, C., Villaz, M., and Florman, H.M. (1998). Pharmacological properties of the T-type calcium current of mouse spermatogenic cells. *Mol. Pharmacol.* *53*, 1104–1111.
- Arnoult, C., Zeng, Y., and Florman, H.M. (1996b). ZP3-dependent activation of sperm cation channels regulates acrosomal secretion during mammalian fertilization. *J. Cell Biol.* *134*, 637–645.
- Babcock, D.F., First, N.L., and Lardy, H.A. (1976). Action of ionophore A23187 at the cellular level: separation of effects at the plasma and mitochondrial membranes. *J. Biol. Chem.* *251*, 3881–3886.
- Bailey, J.L., and Storey, B.T. (1994). Calcium influx into mouse spermatozoa activated by solubilized mouse zona pellucida, monitored with the calcium fluorescent indicator, fluo-3. Inhibition of the influx by three inhibitors of the zona pellucida induced acrosome reaction: tyrphostin A48, pertussis toxin, and 3'-quinuclidinyl benzilate. *Mol. Reprod. Dev.* *39*, 297–308.
- Benoff, S., Cooper, G.W., Hurley, I., Mandel, F.S., Rosenfeld, D.L., Scholl, G.M., Gilbert, B.R., and Hershlag, A. (1994). The effect of calcium ion channel blockers of sperm fertilization potential. *Fertil. Steril.* *62*, 606–617.
- Berridge, M.J. (1995). Capacitative calcium entry. *Biochem. J.* *312*, 1–11.
- Berridge, M.J. (1997). Elementary and global aspects of calcium signaling. *J. Physiol.* *499*, 291–306.
- Blackmore, P.F. (1993). Thapsigargin elevates and potentiates the ability of progesterone to increase intracellular free calcium in human sperm: possible role of perinuclear calcium. *Cell Calcium* *14*, 53–60.
- Bleil, J.D., and Wassarman, P.M. (1983). Sperm-egg interactions in the mouse: sequence of events and induction of the acrosome reaction by a zona pellucida glycoprotein. *Dev. Biol.* *95*, 317–324.
- Bleil, J.D., and Wassarman, P.M. (1986). Autoradiographic visualization of the mouse egg's sperm receptor bound to sperm. *J. Cell Biol.* *102*, 1363–1371.
- Crabtree, G.R. (1999). Generic signals and specific outcomes: signaling through  $\text{Ca}^{2+}$ , calcineurin, and NF-AT. *Cell* *95*, 611–614.
- Darszon, A., Labarca, P., Nishigaki, T., and Espinosa, F. (1999). Ion channels in sperm physiology. *Physiol. Rev.* *79*, 481–510.
- Espinosa F., Lopez-Gonzalez, I., Serrano, C.J., Gasque, G., de la Vega-Beltran, J.L., Trevino, C.L., and Darszon, A. (1999). Anion channel blockers differentially affect T-type  $\text{Ca}^{2+}$  currents of mouse spermatogenic cells,  $\alpha 1\text{E}$  currents expressed in *Xenopus* oocytes and the sperm acrosome reaction. *Dev. Gen.* *25*, 103–114.
- Fagan, K.A., Mons, N., and Cooper, D.M.F. (1998). Dependence of the  $\text{Ca}^{2+}$ -inhibitable adenylyl cyclase of C6–2B glioma cells on capacitative  $\text{Ca}^{2+}$  entry. *J. Biol. Chem.* *273*, 9297–9305.
- Fanger, C.M., Hoth, M., Crabtree, G.R., and Lewis, R.G. (1995). Characterization of T cell mutants with defects in capacitative calcium entry: genetic evidence for the physiological roles of CRAC channels. *J. Cell Biol.* *131*, 655–667.
- Florman, H.M. (1994). Sequential focal and global elevations of sperm intracellular  $\text{Ca}^{2+}$  are initiated by the zona pellucida during acrosomal exocytosis. *Dev. Biol.* *165*, 152–164.
- Florman, H.M., Arnoult, C., Kazam, I.G., Li, C., and O'Toole, C.M.B. (1999). An intimate biochemistry: egg-regulated acrosome reactions of mammalian sperm. *Adv. Dev. Biochem.* *5*, 147–186.
- Florman, H.M., Corron, M.E., Kim, T.D.-H., and Babcock, D.F. (1992). Activation of voltage-dependent calcium channels of mammalian sperm is required for zona pellucida-induced acrosomal exocytosis. *Dev. Biol.* *152*, 304–314.
- Florman, H.M., Tombes, R.M., First, N.L., and Babcock, D.F. (1989). An adhesion-associated agonist from the zona pellucida activates G protein-promoted elevations of internal Ca and pH that mediate mammalian sperm acrosomal exocytosis. *Dev. Biol.* *135*, 133–146.
- Fomina, A.F., and Nowycky, M.C. (1999). A current activated on depletion of intracellular  $\text{Ca}^{2+}$  stores can regulate exocytosis in adrenal chromaffin cells. *J. Neurosci.* *19*, 3711–3722.
- Fraser, L.R., Abeydeera, L.R., and Niwa, K. (1995).  $\text{Ca}^{2+}$  regulating mechanisms that modulate bull sperm capacitation and acrosomal exocytosis as determined by chlortetracycline analysis. *Mol. Reprod. Dev.* *40*, 233–241.
- Garcia, R.L., and Schilling, W.P. (1997). Differential expression of mammalian TRP homologues across tissue and cell lines. *Biochem. Biophys. Res. Commun.* *239*, 279–283.
- Gordon, M. (1973). Localization of phosphatase activity on the membranes of the mammalian sperm head. *J. Exp. Zool.* *185*, 111–119.
- Gordon, M., Dandekar, P.V., and Eager, P.R. (1978). Identification of phosphatases on the membranes of guinea pig sperm. *Anat. Rec.* *191*, 123–133.
- Gryniewicz, G., Poenie, M., and Tsien, R.Y. (1985). A new generation of  $\text{Ca}^{2+}$  indicators with greatly improved fluorescence properties. *J. Biol. Chem.* *260*, 3440–3450.
- Guerrero, A., and Darszon, A. (1989). Evidence for the activation of two different  $\text{Ca}^{2+}$  channels during the egg jelly-induced acrosome reaction of sea urchin sperm. *J. Biol. Chem.* *264*, 19593–19599.
- Hagiwara, S., and Kawa, K. (1984). Calcium and potassium currents in spermatogenic cells dissociated from rat seminiferous tubules. *J. Physiol.* *356*, 135–149.
- Hershlag, A., Cooper, G.W., and Benoff, S. (1995). Pregnancy following discontinuation of a calcium channel blocker in the male partner. *Hum. Reprod.* *10*, 599–606.
- Hille, B. (1992). *Ionic Channels in Excitable Membranes*, Sunderland, MA: Sinauer Press.
- Hopf, F.W., Reddy, P., Hong, J., and Steinhardt, R.A. (1996). A capacitative calcium current in cultured skeletal muscle cells is mediated by the calcium-specific leak channel and inhibited by dihydropyridine compounds. *J. Biol. Chem.* *271*, 22358–22367.
- Inoue, S., and Spring, K.R. (1997). *Video Microscopy: The Fundamentals*, New York: Plenum Press, 513–514.
- Kline, D., and Kline, J.T. (1992). Thapsigargin activates a calcium influx pathway in the unfertilized mouse egg and suppresses repetitive calcium transients in the fertilized egg. *J. Biol. Chem.* *267*, 17624–17630.

- Lee, M.A., and Storey, B.T. (1989). Endpoint of the first stage of the zona pellucida-induced acrosome reaction in mouse spermatozoa characterized by acrosomal H<sup>+</sup> and Ca<sup>2+</sup> permeability: population and single cell kinetics. *Gamete Res.* 24, 303–326.
- Li, H.-S., Xu, X.Z.-S., and Montell, C. (1999). Activation of a TRPC3-dependent cation current through the neurotrophin BDNF. *Neuron* 24, 261–273.
- Liévano, A., Santi, C.M., Serrano, J., Treviño, C.L., Bellve, A.R., Hernandez-Cruz, A., and Darszon, A. (1996). T-type Ca<sup>2+</sup> channels and alpha 1E expression in spermatogenic cells, and their possible relevance to the sperm acrosome reaction. *FEBS Lett.* 388, 150–154.
- Liman, E.R., Corey, D.P., and Dulac, C. (1999). TRP2: a candidate transduction channel for mammalian pheromone sensory signaling. *Proc. Natl. Acad. Sci. USA* 96, 5791–5796.
- Meizel, S., and Turner, K.O. (1993). Initiation of the human sperm acrosome reaction by thapsigargin. *J. Exp. Zool.* 267, 350–355.
- Merritt, J.E., Jacob, R., and Hallam, T.J. (1989). Use of manganese to discriminate between calcium influx and mobilization from internal stores in stimulated human neutrophils. *J. Biol. Chem.* 264, 1522–1527.
- Murase, T., and Roldan, E.R.S. (1996). Progesterone and the zona pellucida activate different transducing pathways in the sequence of events leading to diacylglycerol generation during mouse sperm acrosomal exocytosis. *Biochem. J.* 320, 1017–1023.
- Parekh, A.B., and Penner, R. (1997). Store depletion and calcium influx. *Physiol. Rev.* 77, 901–930.
- Patterson, R.L., van Rossum, D.B., and Gill, D.L. (1999). Store-operated Ca<sup>2+</sup> entry: evidence for a secretion-like coupling model. *Cell* 98, 487–499.
- Petersen, O.H. (1996). Can Ca<sup>2+</sup> be released from secretory granules or synaptic vesicles? *Trends Neurosci.* 19, 411–413.
- Philipp, S., Hambrecht, S., Braslavski, L., Schroth, G., Freichel, M., Murakami, M., Cavalie, A., and Flockerzi, V. (1998). A novel capacitative calcium entry channel expressed in excitable cells. *EMBO J.* 17, 4274–4282.
- Putney, J.W. (1977). Muscarinic, alpha-adrenergic and peptide receptors regulate the same calcium influx sites in the parotid gland. *J. Physiol.* 268, 139–149.
- Putney, J.W. (1986). A model for receptor-regulated calcium entry. *Cell Calcium* 7, 1–12.
- Roldan, E.R.S., Murase, T., and Shi, Q.-X. (1994). Exocytosis in spermatozoa in response to progesterone and zona pellucida. *Science* 266, 1578–1581.
- Santi, C.M., Darszon, A., and Hernandez-Cruz, A. (1996). A dihydropyridine-sensitive T-type Ca<sup>2+</sup> current is the main Ca<sup>2+</sup> current carrier in mouse primary spermatocytes. *Am. J. Physiol.* 271, C1583–C1593.
- Santi, C.M., Santos, T., Hernandez-Cruz, A., and Darszon, A. (1998). Properties of a novel pH-dependent Ca<sup>2+</sup> permeation pathway present in male germ cells with possible roles in spermatogenesis and mature sperm function. *J. Gen. Physiol.* 112, 33–53.
- Shirakawa, H., and Miyazaki, S. (1999). Spatiotemporal characterization of intracellular Ca<sup>2+</sup> rise during the acrosome reaction of mammalian sperm induced by zona pellucida. *Dev. Biol.* 208, 70–78.
- Spungin, B., and Breitbart, H. (1996). Calcium mobilization and influx during sperm exocytosis. *J. Cell Sci.* 109, 1947–1955.
- Takemura, H., and Putney, J.W. (1989). Capacitative calcium entry in parotid acinar cells. *Biochem. J.* 258, 409–412.
- Tesarik, J., Carreras, A., and Mendoza, C. (1993). Differential sensitivity of progesterone- and zona pellucida-induced acrosome reactions to pertussis toxin. *Mol. Reprod. Dev.* 34, 183–189.
- Thaler, C.D., and Cardullo, R.A. (1995). Biochemical characterization of a glycosylphosphatidylinositol-linked hyaluronidase on mouse sperm. *Biochemistry* 34, 7788–7795.
- Thastrup, O., Dawson, A.P., Scharff, O., Foder, B., Cullen, P.J., Drobak, B.K., Bjerrum, P.J., Christensen, S.B., and Hanley, M.R. (1989). Thapsigargin, a novel molecular probe for studying intracellular calcium release and storage. *Agents Actions* 27, 17–23.
- Thomas, P., and Meizel, S. (1989). Phosphatidylinositol 4,5-bisphosphate hydrolysis in human sperm stimulated with follicular fluid or progesterone is dependent upon Ca<sup>2+</sup> influx. *Biochem. J.* 264, 539–546.
- Tomes, C.N., McMaster, C.R., and Saling, P.M. (1996). Activation of mouse sperm phosphatidylinositol-4,5 bisphosphate-phospholipase C by zona pellucida is modulated by tyrosine phosphorylation. *Mol. Reprod. Dev.* 43, 196–204.
- Trevino, C.L., Santi, C.M., Beltran, C., Hernandez-Cruz, A., Darszon, A., and Lomeli, H. (1998). Localization of inositol trisphosphate and ryanodine receptors during mouse spermatogenesis: possible functional implications. *Zygote* 6, 159–172.
- Walensky, L.D., and Snyder, S.H. (1995). Inositol 1,4,5-trisphosphate receptors selectively localized to the acrosomes of mammalian sperm. *J. Cell Biol.* 130, 857–869.
- Wassarman, P.M. (1999). Mammalian fertilization: molecular aspects of gamete adhesion, exocytosis, and fusion. *Cell* 96, 176–183.
- Yanagimachi, R. (1994). Mammalian fertilization. In: *The Physiology of Reproduction*, ed. E. Knobil and J.D. Neill, New York: Raven Press, 189–317.
- Yao, Y., Ferrer-Montiel, A.V., Montal, M., and Tsien, R.Y. (1999). Activation of store-operated Ca<sup>2+</sup> current in *Xenopus* oocytes requires SNAP-25 but not diffusible messenger. *Cell* 98, 475–485.
- Zapata, O., Ralston, J., Beltran, C., Parys, J., Chen, J.L., Longo, F.J., and Darszon, A. (1997). Inositol trisphosphate receptors in sea urchin sperm. *Zygote* 5, 355–364.
- Zhu, X., Jiang, M., Peyton, M., Boulay, G., Hurst, R., Stephani, E., and Birnbaumer, L. (1996). *Trp*, a novel mammalian gene family essential for agonist-activated capacitative Ca<sup>2+</sup> entry. *Cell* 85, 661–671.
- Zweifach, A., and Lewis, R.S. (1993). Mitogen-regulated Ca<sup>2+</sup> current of T lymphocytes is activated by depletion of intracellular Ca<sup>2+</sup> stores. *Proc. Natl. Acad. Sci. USA* 90, 6295–6299.