Effects of Adenine Nucleotides on Inositol 1,4,5-Trisphosphate-induced Calcium Release in Vascular Smooth Muscle Cells

MASAMITSU IINO

From the Department of Pharmacology, Faculty of Medicine, University of Tokyo, Tokyo 113, Japan

ABSTRACT Effects of adenine nucleotides on the inositol 1,4,5-trisphosphate (IP3)-induced Ca release (ICR) mechanism were studied in smooth muscle cells of the guinea pig portal vein. A microfluorometry method of fura-2 was used to measure Ca release from saponin-skinned thin muscle strips (width ~200 μm, thickness 50–70 μm, length 2–3 mm). About 80% of ionomycin-releasable Ca store was sensitive to IP3, of which ~20% was also sensitive to caffeine. The rate of Ca release by 0.1 μM IP3 depended biphasically on ATP concentration in the absence of Mg2+; it was dose-dependently enhanced by ATP up to ~0.5 mM, and above this concentration the enhancement became smaller. However, the decline of enhancement of the ICR at the higher ATP concentrations was absent at IP3 concentrations >1 μM. This suggests competitive antagonism between IP3 and ATP. Clear effects of ATP were observed not only at pCa 7 or 8, where the Ca-induced Ca release was not activated, but after a ryanodine treatment to excise the functional compartment that possessed the Ca-induced Ca release mechanism. ATP had no effect on the rate of Ca leakage in the absence of IP3 even at pCa 5.5 after the ryanodine treatment. Therefore, ATP has direct biphasic effects on the IP3-induced Ca release mechanism. The Ca release induced by 0.1 μM IP3 at pCa 7 was potentiated not only by ATP, but by 0.5 mM ADP, AMP, or βγ-methyleneadenosine 5′-triphosphate. 0.5 mM GTP had only a little effect on the IP3-induced Ca release. These results extend the functional similarities between Ca- and IP3-induced Ca release mechanisms in that adenine nucleotides enhance Ca release. Millimolar concentration of ATP, which is present physiologically, will shift the dose–response relation of IP3 toward the higher IP3 concentration and enhance the maximal effect of IP3. Thus, ATP is expected to assist the Ca release by higher concentrations of IP3 while having less effect on the Ca release by low levels of IP3. These effects of ATP may be important in the switching of Ca release from the intracellular Ca store by IP3.

INTRODUCTION

Inositol 1,4,5-trisphosphate (IP3) is formed in receptor-coupled signal transduction and is capable of releasing Ca from intracellular stores. This receptor–IP3 pathway

Address reprint requests to Dr. Masamitsu Iino, Department of Pharmacology, Faculty of Medicine, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113, Japan.
has been proposed to be an important mechanism for Ca mobilization in agonist-induced responses in many types of cells, including smooth muscle cells (Berridge and Irvine, 1984). Many studies have then been initiated to look into the physiological modulating factors of the IP₃-induced Ca release (IICR) mechanism, such as Ca²⁺, pH, and nucleotides. It has been shown that Ca²⁺ itself modulates the IICR in a biphasic manner; i.e., Ca²⁺ stimulates the IICR below 300 nM and depresses the IICR above 300 nM (Iino, 1990).

Adenine nucleotides are the important intracellular constituents, and have been reported to modulate the IICR, although some of the results remain controversial. Smith, Smith, and Higgins (1985) noted that ATP or its analogues are required for IP₃-induced Ca efflux from permeabilized cultured smooth muscle cells. On the contrary, it has been demonstrated that IP₃ induces Ca release from the smooth muscle Ca store of skinned smooth muscle fiber bundles in the absence of any nucleotide (Iino, 1987, 1990). In accordance with these results, both aortic smooth muscle sarcoplasmic reticulum vesicles incorporated into planar bilayer and purified cerebellar IP₃ receptor incorporated into lipid vesicles showed Ca channel activities in response to IP₃ in the complete absence of nucleotides (Ehrlich and Watras, 1988; Ferris, Huganir, Supattapone, and Snyder, 1989). On the other hand, adenine nucleotides have been reported to enhance the IICR. Hirata, Kukita, Sasaguri, Suematsu, Hashimoto, and Koga (1985) have shown that ATP enhances the IICR in permeabilized macrophages. In general accordance with their results, I have noted that AMP enhances the IICR in smooth muscle cells (Iino, 1990). This study was conducted, therefore, to further look into the effects of adenine nucleotides on the IICR in saponin-permeabilized smooth muscle cells.

A preliminary account of the study was presented at the Japanese Pharmacological Society Meeting (Iino and Endo, 1989).

M E T H O D S

Apparatus and procedures of the experiments have been described in previous papers (Iino, 1989, 1990). Saponin-skinned thin smooth muscle fiber bundles were fixed in a capillary cuvette (internal diameter 400 μm) through which solutions can be perfused. The amount of Ca released from the specimen was measured by a microfluorometry of ~ 35 μM fura-2 at 20–22°C. The capillary cuvette was illuminated at 340 and 360 nm (or 345 and 365 nm) alternating at 200 Hz, and the fluorescence intensity near 500 nm was measured. Fluorescence intensity with 340 nm (or 345 nm) excitation or the ratios of the fluorescence intensity with 340 nm (or 345 nm) excitation or the ratios of the fluorescence intensity with 340 nm (or 345 nm) to that with 360 nm (or 365 nm) were used as the Ca signals. The results did not depend on the type of these fluorescence signals.

Fiber Bundles

Fiber bundles of portal vein of guinea pig were used in this study. Segments of portal vein (length ~ 10 mm) adjacent to the liver were removed and cut open by a longitudinal incision in a dissecting trough filled with the following external solution (in mM): 150 NaCl, 4 KCl, 2 CaMS₂ (calcium methanesulfonate), 1 MgMS₂, 5 HEPES (N-2-hydroxyethylpiperazine-N’-ethanesulfonic acid), pH 7.4, adjusted with NaOH. The opened wall of the vein was pinned down onto the Silgard bottom of the trough and the endothelial side was rubbed. A thin longitudinal strip (width ~ 200 μm) was then cut and the adventitial layer was removed using fine forceps and scissors. Both ends of a ~ 2.5-mm-long segment with uniform width and thickness (50–70 μm) were then tied with fine silk filament to a stainless steel wire (diameter
Effects of ATP on IP₃-induced Ca Release

100 μm, length ~15 mm). Fiber bundles were treated with saponin (50 μg/ml) in a relaxing solution (solution 1, Table I) for 35 min and then inserted into the capillary cuvette.

Protocol to Measure Nucleotide Dependence of IP₃-induced Ca Release

The experimental protocols are schematically presented in Fig. 1. Protocol 1 was used to study the size of the Ca stores and protocol 2 to analyze the effect of nucleotides on the IICR.

An example of the experiments following protocol 2 is shown in Fig. 2. The records show the fluorescence intensity with 340 nm excitation. At the small vertical bars or arrows the solutions were flushed into the capillary cuvette. Following the flush marked with the bars, there was a slow continuous flow of the same solution to keep the environment constant. After the flush indicated by the arrows, flow of the solution was completely halted to observe the change in the Ca concentration within the cuvette. For the numbering of the solutions, see Table I. 33 μM fura-2 was added to the solutions underlined by the hatched horizontal bars in Fig. 2. The microcuvette was illuminated only when the solutions contained fura-2 to avoid unnecessary irradiation of the skinned fiber bundles with the UV light. Data acquisitions and solution changes were controlled by a microcomputer (Iino, 1989) so that they were precisely synchronized.

The experimental runs proceeded in the following manner. For the solution numbers, refer to Table I. Step 1 (loading): After a 2–3-min preincubation in a relaxing solution (solution 1), Ca store was loaded with Ca at pCa 6 for 3 min in the presence of 4 mM MgATP (solution 2). Step 2 (wash): Both Ca and ATP were removed by a flush of solution 3 (a solution with 1 mM EGTA, 1.5 mM Mg, and no ATP) and perfusion of the same solution for 1 min. This procedure was repeated twice. Step 3 (test): This step was optional, and was included only in protocol 2.

Table I

| Protocol | Solution No. | Name | EGTA or CaEGTA | CaEDTA* | MgMg* | KM | ATP-Na* | AMP | Mg** | K* |
|----------|--------------|------|----------------|---------|--------|----|---------|------|-------|----|
| Loading  | 1 G1         | 1    | 0              | 5.54    | 108.6  | 4.76| 0       | 1.5  | 149   |
|          | 2 pCa6-loading | 0.298 | 0.702         | 5.51    | 108.6  | 4.76| 0       | 1.5  | 149   |
| Wash     | 3 G1R        | 1    | 0              | 1.54    | 134.5  | 0   | 0       | 1.5  | 166   |
| Test     | 4 D1R        | 1.0* | 0              | 0       | 136.5  | 0   | 0       | 0    | 168   |
|          | 5 pCa8RD     | 8.51*| 1.49*          | 0       | 90.7   | 0   | 0       | 0    | 147   |
|          | 6 pCa7RD     | 3.64*| 6.36*         | 0       | 102.9  | 0   | 0       | 0    | 155   |
|          | 6' pCa5.5RD  | 0.18*| 9.83*         | 0       | 111.6  | 0   | 0       | 0    | 151   |
|          | 7 pCa7R      | 8.11 | 1.89          | 1.82    | 107.2  | 0   | 0       | 1.5  | 156   |
|          | 8 G10R       | 10   | 0             | 1.90    | 107.1  | 0   | 0       | 1.5  | 157   |
|          | 8' D10R      | 10*  | 0             | 0       | 86.9   | 0   | 0       | 0    | 144   |
| Assay    | 9 G0RMg0     | 0    | 0             | 0       | 142.1  | 0   | 0       | 0    | 171   |
|          | 10 Assay     | 0    | 0             | 0       | 84.1   | 0   | 25      | 0    | 155   |

Concentrations are in millimolar. All solutions contained 20 mM PIPES (piperazine-N,N'-bis(2-ethanesulfonic acid)) and 20 mM NaNO₃. Solution 10 contained 10 μM IP₃, unless otherwise described. pH was adjusted to 7.0 at 20°C with KOH. Mg** and K* concentrations were estimated by the numerical solution of multi-equilibrium between metals and ligands in the solution. When ATP was present, MgATP* concentration was calculated to be 4.0 mM. Total ionic strength was 200 mM in all the solutions. EGTA, ethylenedinitrilotetraacetic acid; EDTA, ethylenediaminetetraacetic acid; Ms, methanesulfonic acid.
Protocol 1

Step 1: **LOADING**
- ATP, Ca, ADP, Pi
- Ca

Step 2: **WASH**
- Ca

Step 3: **TEST**
- IP3 (or caffeine, or ionomycin)

Step 4: **ASSAY**
- Ca

Protocol 2

Step 1: **LOADING**
- ATP, Ca, ADP, Pi
- Ca

Step 2: **WASH**
- Ca

Step 3: **TEST**
- Stimulus
- IP3

Step 4: **ASSAY**
- Ca

**Figure 1.** Scheme of the experimental protocol. Rounded boxes represent intracellular Ca store. Step 1 (loading): In situ Ca pump ATPase was used to load the store in the presence of 1 μM Ca²⁺ and 4 mM MgATP for 3 min. Step 2 (wash): Both Ca²⁺ and ATP were washed. Step 3 (test): Ca releasing test stimulus was applied in the presence of a high concentration of Ca buffer (EDTA or EGTA). This step is optional (i.e., included only in protocol 2 to study the rate of Ca release). Step 4 (assay): Ca in the store was thoroughly released by a high dose of Ca releasing agent (10 μM IP3, 50 mM caffeine, or 10 μM ionomycin). The amount of released Ca was assayed by the change in the fluorescence intensity of fura-2. For further explanations see text.

**Figure 2.** A typical record of experiments following protocol 2. Fluorescence intensity with 340 nm excitation is shown. Small vertical bars and arrows below the traces indicate the timing of solution changes. The numbers below the traces refer to the solutions listed in Table I. 33 μM fura-2 was added to the solutions only during assay as indicated by the hatched bar, during which the capillary cuvette was illuminated. (A) Control run without test IP3 application. (B) A test run with a 15-s application of 0.1 μM IP3 at pCa 7 as indicated (6*). (C) Amount of Ca release during assay in the control run (a-a') and in the test run (b-b'). Vertical calibration indicates the amount of Ca increase in the cuvette due to Ca release from the skinned fiber bundle. For further explanations see text.
Mg²⁺ was removed by the perfusion for 1 min of solution 4, which contained 1 mM EDTA with no added Mg. Then a test solution that contained IP₃ on top of either solution 6 (or solution 5) was applied for 5–45 s (Fig. 2B). This IP₃ application was omitted in the control runs (Fig. 2A). Solution 4 and the test solution contained the same concentration of a nucleotide. IP₃ was then removed by the application of solution 8 that contained 10 mM EGTA instead of EDTA, 1.5 mM Mg²⁺, and no Ca. Step 4 (assay): Fura-2 was then introduced in solution 3 for 1 min. Then both EGTA and Mg²⁺ were removed by solution 9 in the continued presence of fura-2 (1 min). Because fura-2 was the only Ca buffer in this solution, the fluorescence intensity increased here due to contaminating ~3 μM total Ca. Finally, 10 μM IP₃ (or in some experiments 50 mM caffeine or 10 μM ionomycin) was applied to discharge Ca in the store, and the resulting change in the fluorescence intensity of fura-2 was measured (for 70–180 s). The assay solution was then replaced by solution 3.

To obtain the baseline Ca level of the assay solution, steps 3 and 4 were repeated without the Ca loading. The resulting Ca signal (a' and b' of Fig. 2) was subtracted from the initial assay (a and b of Fig. 2) to obtain the amount of Ca released from the store (Fig. 2C). At the end of the experiment the fluorescence intensities of the assay solutions with 100 μM Ca and 1 mM EGTA were separately obtained. The difference between these measurements corresponded to the Ca concentration change equal to the fura-2 concentration, and was used to calibrate the increase in the total Ca concentration within the cuvette due to Ca release from the skinned fiber. Linearity of the measurement is excellent and has been discussed elsewhere (Iino, 1989).

Experiments following these protocols can be repeated many times in one fiber bundle unless ionomycin is used, which causes irreversible loss of the Ca uptake capacity. In protocol 2, if one compares the amount of Ca assayed at step 4 with and without the application of the test solution in step 3 as shown in Fig. 2C, the amount of Ca released during the test procedure can be measured. The advantage of this protocol is that the condition for the IICR can be strictly controlled in step 3, especially with a high concentration of a Ca buffer.

Solutions

The main experimental solutions are listed in Table I. Compositions of the solutions were calculated as described previously (Iino, 1989, 1990). The total ionic strength of the solutions was adjusted to 200 mM. Nucleotides were simply added to the appropriate solutions when their concentration was less than or equal to 0.5 mM. Above this concentration, the amount of potassium methanesulfonate (KMs) was reduced to keep the total ionic strength constant. ATP and ADP were obtained from Boehringer Mannheim GmbH, Mannheim, Germany. AMP, adenine, B,γ-methyleneadenosine 5′-triphosphate (AMPOPCP), and IP₃ were purchased from Sigma Chemical Co. (St. Louis, MO), ionomycin from Calbiochem Corp. (La Jolla, CA), saponin from ICN Pharmaceuticals Inc. (Cleveland, OH), ryanodine from Agrysystems International (Wind Gap, PA), and fura-2 from Molecular Probes, Inc. (Eugene, OR). All other chemicals were of the highest reagent grade.

Statistics

Statistical significance was tested using the t test. When paired observations were to be compared, the paired t test was used.

RESULTS

Compartments of the Ca Store

Our previous studies demonstrated the presence of two functional compartments in the smooth muscle Ca store (Iino, 1987, 1989, 1990; Iino, Kobayashi, and Endo,
One of the functional compartments, designated as S₀, has both Ca-induced Ca release (CICR) and IICR mechanisms. Since caffeine induces Ca release by increasing the Ca sensitivity of the CICR mechanism, S₀ is sensitive to both caffeine and IP₃ (Iino, 1989). The rest of the store, S₈, has only the IICR, and therefore is insensitive to caffeine. The traces without asterisks in Fig. 3 A show the superimposed traces of Ca release by either 10 μM IP₃ or 50 mM caffeine in skinned fiber bundles of portal vein after the Ca loading at pCa 6 for 3 min (protocol 1, see Methods). Caffeine releases ~20% or less (18.5 ± 11.2%, mean ± SD, n = 12) of the IP₃-sensitive store and the remaining >80% of the store is sensitive only to IP₃.

A plant alkaloid, ryanodine has been shown to lock the CICR channels of the striated muscle in an open state (Fleischer, Ogunbunmi, Dixon, and Fleer, 1985; Rousseau, Smith, and Meissner, 1987). Ryanodine seems to have the same effect on the CICR channels of smooth muscle, and removes the Ca uptake capacity of S₀ in

![Figure 3](image-url)
Effects of ATP on IP$_3$-induced Ca Release

IINO

687

guinea pig taenia caeci by making this functional compartment permanently hyper-permeable to Ca (Iino et al., 1988; Iino, 1990). The effect of ryanodine on the smooth muscle cells of guinea pig portal vein was examined. In Fig. 3A, caffeine- and IP$_3$-releasable Ca were compared before and after a 30-μM ryanodine treatment for 2 min at pCa 5.7 in the presence of 45 mM caffeine and 22.5 mM AMP. After the ryanodine treatment (traces marked with *), caffeine failed to induce rapid Ca release. The remaining creeping signal was not due to enhancement of the CICR, because the same rate of Ca release was obtained by the application of a blank assay solution without caffeine or IP$_3$ (trace marked with **) and would represent simple Ca leakage from S$. A similar rate of Ca leakage was observed before the ryanodine treatment or with a blank assay solution without AMP (not shown). After the ryanodine treatment, the amount of Ca released by IP$_3$ declined by almost the same extent as the decrease in the caffeine-releasable Ca. These results show that the ryanodine treatment specifically removes the function of S$ in the portal vein smooth muscle cells.

Since Ca in S$ may be released through the two Ca release mechanisms, the interpretation of the results may become complicated when one tries to study the IICR mechanism at Ca$^{2+}$ concentrations > 1 μM, where the CICR mechanism becomes activated (Iino, 1989). To circumvent this problem, fiber bundles obtained from guinea pig taenia caeci were treated in a previous study with ryanodine to excise the function of S$ at the beginning of the experiments so that the IICR mechanism could be studied independently of the CICR (Iino, 1990). In this study portal vein smooth muscle cells were used to study the effect of nucleotides on the IICR. Because the proportion of S$ is smaller than that of taenia (~20% vs. ~40% in taenia caeci), and because the effect on the IICR was studied at either pCa 8 or 7, which was too low for the CICR to become active (Iino, 1989), no ryanodine pretreatment was carried out in most of the experiments. The presence of the CICR did not affect the conclusions as will be shown later.

Fig. 3B compares the amount of Ca released within 2 min by 10 or 30 μM IP$_3$ in the presence and the absence of 25 mM AMP; i.e., solutions 10 and 9 (Table I), respectively. If a small amount of run-down is allowed for, 10 μM IP$_3$ with 25 mM AMP releases about the same amount of Ca that is released by 30 μM IP$_3$ with or without 25 mM AMP. 10 μM IP$_3$ without AMP may release a few percent less Ca within this period than the other stimuli. In the following, therefore, 10 μM IP$_3$ with 25 mM AMP was used as a standard stimulus to deplete the IP$_3$-sensitive Ca store. The reason why AMP enhances 10 μM IP$_3$-induced Ca release will be presented later.

Since IP$_3$ is a polyanion, its binding to the receptor is expected to be highly dependent on the ionic strength. To keep the total ionic strength constant, there were inevitable changes in the osmolarity and K$^+$ concentration among the experimental solutions. The solution with the greatest osmolarity was solution 10, and its osmolarity was ~15% greater than that of solution 9 with the smallest value. There was a ~10% difference in the K$^+$ concentration between the two solutions. However, as shown in Fig. 3B, the amount of IP$_3$-releasable Ca was the same in either solution when the maximum dose of IP$_3$ was used. Therefore, the variation in the osmolarity and K$^+$ concentration within the range of the current study had no effect on the size of Ca release.

To estimate the proportion of the IP$_3$-sensitive compartment in the total Ca store,
the amount of Ca released by IP$_3$ was compared with that released by a high concentration of a Ca ionophore using protocol 1. As shown in Fig. 4A, the size of IP$_3$-releasable Ca was ~80% of the 10 μM ionomycin-releasable Ca in skinned fiber bundles of portal vein smooth muscle. After the ionomycin treatment, IP$_3$ failed to release Ca even after the same Ca loading step. This indicated that ionomycin irreversibly destroyed the Ca holding capacity of the Ca stores. In Fig. 4, B and C, the difference between the sizes of IP$_3$- and ionomycin-releasable stores was studied in a different way using modified protocol 1. After Ca loading at 1 μM Ca for 3 min, Ca assay (step 4) with 10 μM IP$_3$ was immediately followed by a repetition of the Ca assay with either 10 μM IP$_3$ (B) or 10 μM ionomycin (C). The second application of IP$_3$ did not release Ca (because Ca loading was not carried out between the assays), but under the same condition ionomycin released Ca which was left unreleased after the application of IP$_3$. The amount of this Ca release was equal to ~20% of the IP$_3$-releasable Ca (Fig. 4 C). This again indicates that not all of the total Ca store, but a large fraction of it, was sensitive to IP$_3$. A 50-mM caffeine assay carried out immediately after the IP$_3$ assay failed to release Ca (not shown), as was the case in taenia caeci (Iino, 1987, 1990).

**Effect of ATP on the Time Course of the IICR**

Fig. 5 shows the time course of 1 μM IP$_3$-induced Ca release at pCa 7 obtained using protocol 2. In each skinned fiber, three test runs with 1 μM IP$_3$ application in step 3 were bracketed by two control runs without the test IP$_3$ applications as shown in Fig. 5 A. Compared with the control runs, the amounts of Ca assayed were smaller in the
test runs. If the duration of IP₃ application during step 3 was increased, less Ca was assayed. The data points were normalized to the average amount of Ca assayed in the control runs. The compiled results are shown in Fig. 5 B. These results indicate that Ca was released roughly exponentially during step 3 upon application of IP₃ (open circles). The time course of Ca release was faster when the test IP₃ was applied in the presence of 0.5 mM ATP without Mg (solid circles). If the test solution did not contain IP₃, the Ca in the store declined only very slowly and was independent of the presence or absence of ATP (solid and open triangles, respectively). This slow Ca leakage seems to correspond to the creeping signal marked with ** in Fig. 3 A. These results demonstrate that ATP enhances the IICR, although ATP neither induces Ca release by itself nor enhances the CICR at pCa 7.

![Figure 5](image)

**Figure 5. Effects of ATP on the time course of IP₃-induced Ca release.** (A) An example of the experiments (protocol 2) to study the time course of the IP₃-induced Ca release. Ca release records during step 4 of 5 consecutive runs are shown. The first and the fifth runs were the controls without stimulus application in step 3. From the second to the fourth runs, 1 μM IP₃ was applied for 45, 15, or 5 s at pCa 7 (solution 6) in the presence of 0.5 mM ATP in step 3. The order of the test runs was shuffled among different experiments. (B) The amount of Ca assayed in step 4 after the application of a test solution for the duration shown in the abscissa is shown. The data points were normalized to the average of the control runs in each fiber. The test solution contained 1 μM IP₃ without ATP (open circles, n = 3), 1 μM IP₃ with 0.5 mM ATP (solid circles, n = 4), no IP₃ without ATP (open triangles, n = 5), or no IP₃ with 0.5 mM ATP (solid triangles, n = 5). All the test solutions were at pCa 7 (solution 6). Mean ± SEM.

In this and the following figures, the test IP₃ application in protocol 2 was carried out in the absence of Mg²⁺. This was to inhibit the intrinsic IP₃ phosphatase which absolutely requires Mg²⁺ for its activity, so that the secondary effect of the nucleotides through its possible effect on the enzyme can be excluded.

**Dose–Response Relation of the ATP Effect on the IICR**

The range of ATP concentration effective on the rate of IICR was then studied. Fig. 6 shows the amount of Ca released from the store by a 15-s application of 0.1 μM IP₃ at pCa 7 in the presence of ATP concentration shown on the abscissa. The data were
normalized within each skinned fiber by dividing the amount of Ca release by that without ATP. A total of 19 fibers were used to construct the curve, and on average a 15-s application of IP₃ without ATP released 37 ± 7% (mean ± SD) of Ca in the store. The effect of ATP (circles) was found to be biphasic. Up to ~0.2–0.5 mM, ATP enhanced the Ca release induced by 0.1 μM IP₃ (P < 0.001, 0 vs. 0.2 or 0.5 mM ATP). At concentrations > 0.5 mM, ATP enhancement of IICR declined (P < 0.001, 0.5 vs. 5 mM ATP).

AMP mimicked the enhancing effect of ATP (Fig. 6, squares). The results are expressed in the same way as for ATP, and a 15-s application of 0.1 μM IP₃ without AMP released 38 ± 4% (mean ± SD, n = 6) of Ca in the store in the fibers used for this analysis. Compared with ATP, nearly 100 times higher concentrations of AMP were required to obtain a similar potentiating effect. Up to 25 mM, the highest concentration tested, no obvious inhibitory effect was detected for AMP. This effect of AMP seems to be responsible for the potentiation of 10 μM IP₃-induced Ca release by the nucleotide seen in Fig. 3 B.

**FIGURE 6.** Effects of ATP and AMP on the rate of IICR. 0.1 μM IP₃ was applied for 15 s at pCa 7 with either ATP (circles) or AMP (squares) at the concentration indicated on the abscissa in step 3 of protocol 2. The amount of Ca release was normalized within each fiber by that released with 0.1 μM IP₃ in the absence of any nucleotide. Each data point represents the mean of five to six experiments and SEM.

The Effect of ATP on the HCR with a Higher Concentration of EDTA or after a Ryanodine Treatment

Adenine nucleotides have been shown to enhance the CICR, another Ca release mechanism present in the smooth muscle (Iino, 1989). Removal of Mg²⁺ during the test IP₃ application is also expected to enhance the CICR. Because the experiments here were carried out in the presence of a high concentration of Ca buffer and at very low concentrations of Ca²⁺ where the CICR was not active, the effect of adenine nucleotides on the IICR is unlikely to be affected by their effect on the CICR. Furthermore, the fraction of SO₃ that has the CICR was only ~20% or less of the IP₃-sensitive store (Fig. 3 A). To strengthen these arguments, the effect of ATP was observed either in the presence of a higher concentration of EDTA (20 mM) to obtain a better control of Ca²⁺ during the test IP₃ application, or after a ryanodine treatment to reduce the fraction of SO₃ that possessed the CICR mechanism to zero (see Fig. 3 A; Iino, 1990).
The amount of Ca released by a 15-s application of 0.1 \( \mu \text{M} \) IP\(_3\) in the presence of 0, 0.5, and 5 mM ATP at pCa 7 was compared in Fig. 7 under three conditions; i.e., 10 mM EDTA used as the Ca buffer (open columns), 20 mM EDTA used as the Ca buffer (hatched columns), and 10 mM EDTA used after the same ryanodine treatment used in Fig. 3A (shaded columns). Under any of these conditions 0.1 \( \mu \text{M} \) IP\(_3\) released a greater amount of Ca with 0.5 mM ATP than without ATP \((P < 0.001)\). In addition, the amount of Ca release declined when the ATP concentration was increased from 0.5 to 5 mM \((P < 0.01)\).

To examine the completeness of the ryanodine treatment, CICR at pCa 5.5 (solution 6') was studied before and after the ryanodine treatment (Fig. 8). Experiments were carried out following protocol 2. The test solutions contained 3 \( \mu \text{M} \) Ca\(^{2+}\), no IP\(_3\), and either 0, 0.05, 0.5, or 5 mM ATP, and were washed with solution 8'. As shown by the open circle in Fig. 8, 3 \( \mu \text{M} \) Ca released \( \sim 7\% \) of Ca in the store within 15 s in the absence of ATP and Mg. The CICR was enhanced with ATP at 5 mM \((P < 0.01)\) in accordance with previous results (Iino, 1989). The amount of Ca-induced Ca release is small even with 5 mM ATP, because the average size of the functional compartment with the CICR mechanism (\(S_{\alpha}\)) is only \( \sim 18\% \) of the IP\(_3\)-sensitive store. However, the same Ca treatment failed to induce Ca release after the ryanodine treatment (solid circles) even at 5 mM ATP. None of the data points after the ryanodine treatment were statistically different from zero \((P > 0.1)\). Similar results were obtained when a nonhydrolyzable ATP analogue (AMPOPCP) was used in the place of ATP (not shown). Together with the absence of caffeine-induced Ca release after the ryanodine treatment (Fig. 3A), these results provide clear evidence that the ryanodine treatment completely abolished the function of the compartment with the CICR.

The above results strongly indicate that the biphasic effect of ATP on the IICR is independent of the effect of ATP on the CICR, and that ATP has a direct influence on the IICR.
The Effects of ATP on the Dose–Response Relation of the IICR

To find out if the inhibitory component of the ATP effect could be overcome by the increase in the IP$_3$ concentration, the amount of Ca release within the 15-s application of 0.1–10 μM IP$_3$ was determined at 0, 0.5 and 5 mM ATP (Fig. 9). The ATP concentrations were such that the enhancement and inhibition of the IICR were clearly seen at 0.1 μM IP$_3$. The Ca$^{2+}$ concentration during the test IP$_3$ application in step 3 of protocol 2 was pCa 8, so that the rate of IICR was about three times smaller than that at pCa 7 (Iino, 1990). This was necessary for reliable measurement of Ca release with the higher doses of IP$_3$.

At all the IP$_3$ concentrations tested, 0.5 mM ATP enhanced the IICR ($P < 0.001$). At 0.1 μM IP$_3$, the increase in the ATP concentration from 0.5 to 5 mM reduced the amount of Ca release ($P < 0.02$), in accordance with the results at pCa 7 (Fig. 6). However, the difference between the effects of 0.5 and 5 mM ATP became insignificant at 0.3 and 1 μM IP$_3$ ($P > 0.3$ and $P > 0.05$, respectively). Indeed, the
Effects of ATP on IP₃-induced Ca Release

The effect was clearly reversed at 10 μM IP₃, where the amount of Ca release was greater with 5 mM ATP than with 0.5 mM ATP (P < 0.001). Because the reduction of the potentiating effect at the higher ATP concentrations was overcome by the increase in the IP₃ dose, the negative component of the ATP effect appears to be that of a competitive inhibitor.

Effects of Other Nucleotides on the IICR

Effects of other nucleotides (0.5 mM) on the IICR were studied. The results were normalized in each fiber bundle and compiled in Fig. 10. A 15-s application of 0.1 μM IP₃ at pCa 7 in the absence of Mg²⁺ released, on average, 40% of Ca from the store in the fibers studied (40 ± 11%, mean ± SD, n = 13). ATP, ADP, AMP, and AMPPOCP had a clear enhancing effect (P < 0.001). ATP alone had no Ca releasing action (see Fig. 5). Adenine and GTP had only a very small effect. Therefore, the enhancing effect on IICR seems to be rather specific to adenine nucleotides.

Effect of ATP on the IICR in the Presence of Mg²⁺

So far the effects of ATP on the IICR have been studied in the absence of Mg²⁺. Effects of ATP on the IICR were also studied in the presence of 1.5 mM Mg²⁺ at pCa 7 in six fiber bundles. 1 μM IP₃ released 46 ± 3% (mean ± SEM) of Ca in the store within 45 s. The same dose of IP₃ released 69 ± 5% and 81 ± 3% of Ca in the store in the presence of 0.5 and 5 mM ATP, respectively.

DISCUSSION

This study has demonstrated that adenine nucleotides potentiate the Ca release induced by IP₃ in vascular smooth muscle cells. Evidence has been presented that the results are not indirect consequences of the effects of the nucleotides on the CICR. (a) Clear effects of adenine nucleotides on the IICR are observed at pCa 7 or 8, one to two orders of magnitude lower than the Ca²⁺ concentration required to activate the CICR (Iino, 1989), while ATP alone does not induce Ca release under these conditions. (b) Increasing EDTA concentration during test IP₃ application to 20 mM
from 10 mM did not affect the enhancement of IICR by ATP (Fig. 7). This argues against the possibility that Ca buffering during IP₃-induced Ca release was insufficient. The same results were obtained (Fig. 7) even when the experiments were carried out after the ryanodine treatment which was shown to completely abolish the CICR (Figs. 3 A and 8).

Since clear effects of the nucleotides were seen in the absence of Mg²⁺, the potentiation seems to be independent of the effect of adenine nucleotides on the metabolism of IP₃ by IP₃-phosphatase, which requires Mg²⁺ for its activity (Downes, Mussat, and Michell, 1982). Nor is it likely to be due either to IP₃-kinase activity or protein kinase activities, because adenine nucleotides other than ATP, including nonhydrolyzable AMPOPCP, were also effective. Therefore, there seem to be adenine nucleotide binding sites either on the IP₃ receptor/channels or on the associated proteins. While this manuscript was in preparation, nucleotide dependence of Ca flux into the lipid vesicles reconstituted with purified IP₃ receptors prepared from rat cerebellum was reported (Ferris, Huganir, and Snyder, 1990). Their results are in general agreement with the present results in terms of the enhancement of the IICR, and suggest that the nucleotide binding site is located on the IP₃ receptor itself. The enhancing effect of ATP was also observed in the presence of 1.5 mM Mg²⁺, although a quantitative comparison was difficult because of the presence of intrinsic Mg-dependent IP₃-phosphatase (Iino, 1990). Since ATP has been reported to inhibit IP₃-phosphatase (Hansen, Johanson, Williamson, and Williamson, 1987), the nucleotide may partly enhance the IICR by increasing the effective IP₃ concentration in the presence of Mg²⁺.

We must assume at least one ATP binding site associated with the enhancement of the Ca release mechanism. At higher ATP concentrations (> 0.5 mM) the enhancing effect on the rate of Ca release induced by 0.1 μM IP₃ became smaller. This suggests that there is a secondary ATP binding site with a lower affinity that exerts a negative effect on the IICR. One of the possibilities is that ATP binding to the secondary site may just neutralize the potentiating effect of the high affinity site. However, the decrease in the enhancing effect of ATP became less at higher IP₃ concentrations and was absent at 10 μM IP₃ (Fig. 9). Therefore, a simple neutralizing site cannot explain the negative effect. The disappearance of the negative effect of ATP at higher IP₃ concentrations suggests that ATP may compete with IP₃ on the IP₃ binding site of the receptor. It has been reported that ATP near millimolar concentrations inhibits binding of IP₃ to the receptors (Guillemette, Balla, Bunkal, and Catt, 1987). On the contrary, Ferris et al. (1990) found that the decrease in the enhancing effect of ATP on the IP₃-induced Ca flux in reconstituted vesicles remained even at 100 μM IP₃, and concluded that the effect was not due to competitive antagonism. The discrepancy could be due to differences between smooth muscle and cerebellum. It could also be due to differences between a physiological system and a reconstituted system. It is conceivable that inhibition of IP₃ binding by ATP requires separate associate protein(s) that are lost during the purification procedure.

I cannot provide a definite reason why Smith et al. (1985) found the adenine nucleotide "requirement" for the IICR. One of the possibilities may be that the potency of IP₃ was rather low in their experimental system and Ca release was detected only when the IICR was potentiated by the nucleotides. Since they measured
Effects of ATP on IP$_3$-induced Ca Release

In the presence of 5 mM total Mg, there could have been at least three mechanisms for the potentiation of the IICR by ATP; i.e., (a) direct potentiating effect on the IICR, (b) direct inhibition of intrinsic IP$_3$-phosphatase (Hansen et al., 1987), and (c) indirect inhibition of IP$_3$-phosphatase by the decrease in the free Mg$^{2+}$ concentration (Downes et al., 1982) due to chelation of the metal ions by ATP.

Possible Physiological Significance of the Effects of ATP

$^{31}$P nuclear magnetic resonance spectra of smooth muscle bundles were measured to study nucleotide concentration within the cells (Kushmerick, Dillon, Meyer, Brown, Krisanda, and Sweeney, 1986). Intracellular concentration of ATP within the smooth muscle cells was 1–2 mM, and remained nearly constant even during maximal agonist stimulation under an aerobic condition. Therefore, it is unlikely, at least under physiological conditions, that the intracellular ATP concentration should change greatly and regulate the IICR. However, the dual effects of ATP on the IICR may influence the switching of the Ca release by IP$_3$. Thus, a physiological concentration of ATP may enhance the effect of massively released IP$_3$ during agonist–receptor coupling, while it has a less enhancing effect on the low levels of IP$_3$ produced by a basal turn over of the phosphatidylinositol cycle.

Comparison of CICR and IICR Mechanisms

It is interesting that another type of Ca release channel in the Ca store is also dependent on adenine nucleotides at millimolar concentrations. The CICR mechanism is enhanced by adenine nucleotides but not by guanine, cytosine, or thymidine nucleotides in skeletal muscle (Endo, 1985). The CICR in smooth muscle was also potentiated by AMPOPCP with a $K_m$ of ~0.3 mM (Iino, 1989). The effect of adenine nucleotides on the CICR channels seems to be exerted by simple ligand binding, because nonhydrolyzable analogues of ATP are also effective.

Having characterized both Ca- and IP$_3$-induced Ca release mechanisms in a series of experiments on skinned smooth muscle fiber bundles (Iino, 1989, 1990), we find interesting correspondence between the two Ca release mechanisms in the intracellular Ca store (Table II). Ca and IP$_3$ are the activators of the CICR and the IICR, respectively. Although Ca is not essential for the IICR because IP$_3$ can induce Ca release in the presence of 10 mM EGTA without added Ca, Ca can modulate the IICR at submicromolar concentrations (Iino, 1990). On the other hand, IP$_3$ has been shown to modulate at least skeletal muscle CICR in the presence of Ca$^{2+}$, although IP$_3$ alone cannot activate the channel (Suárez-Isla, Irribarra, Oberhauser, Larralde, Bull, Hidalgo, and Jaimovich, 1988). So there is a remarkable resemblance between the activators and modulators. The present study extended the similarity in the properties, and both Ca release mechanisms have been shown to be enhanced by adenine nucleotides but little by guanine nucleotides. For both mechanisms G proteins do not seem to be involved, because both Ca release mechanisms are switched on and off in the absence of GTP. Of course, these Ca release mechanisms are quite distinct as noted by the differential effect of ryanodine or caffeine (Iino et al., 1988; Iino, 1990).

Recently, proteins responsible for the CICR mechanism (ryanodine receptor) in striated muscles and the IICR mechanism (IP$_3$ receptor) in cerebellum have been
purified and their primary structures have been determined (Imagawa, Smith, Coronado, and Campbell, 1987; Inui, Saito, and Fleischer, 1987; Lai, Erickson, Rousseau, Liu, and Meissner, 1988; Supattapone, Worley, Baraban, and Snyder, 1988; Furuichi, Yoshikawa, Miyawaki, Wada, Maeda, and Mikoshiba, 1989; Takeshima, Nishimura, Matsumoto, Ishida, Kangawa, Minamino, Matsuo, Ueda, Hanaoka, Hirose, and Numa, 1989). Both proteins have high molecular weight (~500 and ~300 kD, respectively) and a large putative cytoplasmic domain as well as putative transmembrane segments located toward the COOH terminus end. Segmental similarities in the amino acid sequence have been noted. Furthermore, both proteins seem to form tetramers exhibiting fourfold symmetry on electron microscopic examination (Wagenknecht, Grassucci, Frank, Saito, Inui, and Fleischer, 1989; Chadwick, Saito, and Fleischer, 1990).

We now know that both CICR channels and IICR channels function as Ca channels in the intracellular Ca store, and share not only structural resemblance but also closely related properties in terms of activators and modulators. The two Ca release mechanisms seem to distribute differently among intracellular Ca stores (Iino, 1987, 1989, 1990; Iino et al., 1988). Assignment of physiological roles to these mechanisms awaits further clarification.

The author thanks Prof. M. Endo for discussion and encouragement.

This work was supported by grants from the Ministry of Education, Science, and Culture, Japan.

Original version received 5 July 1990 and accepted version received 15 March 1991.

REFERENCES

Berridge, M. J., and R. F. Irvine. 1984. Inositol trisphosphate, a novel second messenger in cellular signal transduction. Nature. 312:315–321.

Chadwick, C. C., A. Saito, and S. Fleischer. 1990. Isolation and characterization of the inositol trisphosphate receptor from smooth muscle. Proceedings of the National Academy of Sciences, USA. 87:2132–2136.
Downes, C. P., M. C. Mussat, and R. H. Michell. 1982. The inositol trisphosphate phospho-
monoesterase of the human erythrocyte membrane. Biochemical Journal. 203:169–177.
Ehrlich, B. E., and J. Watras. 1988. Inositol 1,4,5-trisphosphate activates a channel from smooth
muscle sarcoplasmic reticulum. Nature. 336:583–586.
Endo, M. 1985. Calcium release from sarcoplasmic reticulum. Current Topics in Membranes and
Transport. 25:181–230.
Ferris, C. D., R. L. Huganir, and S. H. Snyder. 1990. Calcium flux mediated by purified inositol
1,4,5-trisphosphate receptor in reconstituted lipid vesicles is allosterically regulated by adenine
nucleotides. Proceedings of the National Academy of Sciences, USA. 87:2147–2151.
Ferris, C. D., R. L. Huganir, S. Supattapone, and S. H. Snyder. 1989. Purified inositol 1,4,5-
trisphosphate receptor mediates calcium flux in reconstituted lipid vesicle. Nature. 342:87–89.
Fleischer, S., E. M. Ogunbunmi, M. C. Dixon, and E. A. M. Fleer. 1985. Localization of Ca++ release
channels with ryanodine in junctional terminal cisternae of sarcoplasmic reticulum of fast skeletal
muscle. Proceedings of the National Academy of Sciences, USA. 82:7256–7259.
Furuichi, T., S. Yoshikawa, A. Miyawaki, K. Wada, N. Maeda, and K. Mikoshiba. 1989. Primary
structure and functional expression of the inositol 1,4,5-trisphosphate-binding protein P400.
Nature. 342:32–38.
Guillemette, G., T. Balla, A. J. Baukal, and K. J. Catt. 1987. Inositol 1,4,5-trisphosphate binds to a
specific receptor and releases microsomal calcium in the anterior pituitary gland. Proceedings of the
National Academy of Sciences, USA. 84:8195–8199.
Hansen, C. A., R. A. Johanson, M. T. Williamson, and J. R. Williamson. 1987. Purification and
characterization of two types of soluble inositol phosphate 5-phosphomonoesterases from rat brain.
Journal of Biological Chemistry. 262:17319–17326.
Hirata, M., M. Kukita, T. Sasaguri, E. Suematsu, T. Hashimoto, and T. Koga. 1985. Increase in Ca2+
permeability of intracellular Ca2+ store membrane of saponin-treated guinea pig peritoneal
macrophages by inositol 1,4,5-trisphosphate. Journal of Biochemistry. 97:1575–1582.
Iino, M. 1987. Calcium dependent inositol trisphosphate-induced calcium release in the guinea-pig
taenia caeci. Biochemical and Biophysical Research Communications. 142:47–52.
Iino, M. 1989. Calcium-induced calcium release mechanism in guinea pig taenia caeci. Journal of
General Physiology. 94:363–383.
Iino, M. 1990. Biphasic Ca++ dependence of inositol 1,4,5-trisphosphate-induced Ca release in
smooth muscle cells of the guinea pig taenia caeci. Journal of General Physiology. 95:1103–1122.
Iino, M., and M. Endo. 1989. Effects of nucleotides on the inositol 1,4,5-trisphosphate-induced Ca
release. Folia Pharmacologica Japonica. 94:103P. (Abstr.)
Iino, M., T. Kobayashi, and M. Endo. 1988. Use of ryanodine for functional removal of the calcium
store in smooth muscle cells of the guinea-pig. Biophysical and Biochemical Research Communications.
152:417–422.
Imagawa, T., J. S. Smith, R. Coronado, and K. P. Campbell. 1987. Purified ryanodine receptor from
skeletal muscle sarcoplasmic reticulum is the Ca2+-permeable pore of the calcium release channel.
Journal of Biological Chemistry. 262:6460–6463.
Inui, M., A. Saito, and S. Fleischer. 1987. Purification of the ryanodine receptor and identity with feet
structure of junctional terminal cisternae of sarcoplasmic reticulum from fast skeletal muscle.
Journal of Biological Chemistry. 262:1740–1747.
Kushmerick, M. J., P. F. Dillon, R. A. Meyer, T. R. Brown, J. M. Krisanda, and H. L. Sweeney. 1986.
31P NMR spectroscopy, chemical analysis, and free Mg++ of rabbit bladder and uterine smooth
muscle. Journal of Biological Chemistry. 261:14420–14429.
Lai, F. A., H. P. Erickson, E. Rousseau, Q.-Y. Liu, and G. Meissner. 1988. Purification and reconstitution of the calcium release channel from skeletal muscle. *Nature.* 331:315–319.

Rousseau, E., J. S. Smith, and G. Meissner. 1987. Ryanodine modifies conductance and gating behavior of single Ca\(^{2+}\) release channel. *American Journal of Physiology.* 253:C364–368.

Smith, J. B., L. Smith, and B. L. Higgins. 1985. Temperature and nucleotide dependence of calcium release by myo-inositol 1,4,5-trisphosphate in cultured vascular smooth muscle cells. *Journal of Biological Chemistry.* 260:14413–14416.

Suárez-Isla, B. A., V. Irribarra, A. Oberhauser, L. Larralde, R. Bull, C. Hidalgo, and E. Jaimovich. 1988. Inositol (1,4,5)-trisphosphate activates a calcium channel in isolated sarcoplasmic membranes. *Biophysical Journal.* 54:737–741.

Suematsu, E., M. Hirata, T. Hashimoto, and H. Kuriyama. 1984. Inositol 1,4,5-trisphosphate releases Ca\(^{2+}\) from intracellular store sites in skinned single cells of porcine coronary artery. *Biochemical and Biophysical Research Communications.* 120:481–485.

Supattapone, S., P. F. Worley, J. M. Baraban, and S. H. Snyder. 1988. Solubilization, purification, and characterization of an inositol trisphosphate receptor. *Journal of Biological Chemistry.* 263:1530–1534.

Takeshima, H., S. Nishimura, T. Matsumoto, H. Ishida, K. Kangawa, N. Minamino, H. Matsuo, M. Ueda, M. Hanaoka, T. Hirose, and S. Numa. 1989. Primary structure and expression from complementary DNA of skeletal muscle ryanodine receptor. *Nature.* 339:439–445.

Wagenknecht, T., R. Grassucci, J. Frank, A. Saito, M. Inui, and S. Fleischer. 1989. Three-dimensional architecture of the calcium channel/foot structure of sarcoplasmic reticulum. *Nature.* 338:167–170.