Stimulation of cardiac sarcoplasmic reticulum calcium pump by acylphosphatase: relationship to phospholamban phosphorylation.

THE JOURNAL OF BIOLOGICAL CHEMISTRY
Vol. 271, No. 32, Issue of August 9, pp. 19066–19073, 1996

Printed in U.S.A.

Stimulation of Cardiac Sarcoplasmic Reticulum Calcium Pump by Acylphosphatase

RELATIONSHIP TO PHOSPHOLAMBAN PHOSPHORYLATION*

(Received for publication, January 19, 1996, and in revised form, May 20, 1996)

Chiara Nediani, Claudia Fiorillo, Elena Marchetti, Alessandra Pacini, Gianfranco Liguri, and Paolo Nassi‡

From the Dipartimento di Scienze Biochimiche, Università di Firenze, Viale Morgagni 50, 50134 Firenze, Italy

Ca^{2+} transport by cardiac sarcoplasmic reticulum is tightly coupled with the enzymatic activity of Ca^{2+}-dependent ATPase, which forms and decomposes an intermediate phosphoenzyme. Heart sarcoplasmic reticulum Ca^{2+} pump is regulated by cAMP-dependent protein kinase (PKA) phospholamban phosphorylation, which results in a stimulation of the initial rates of Ca^{2+} transport and Ca^{2+} ATPase activity. In the present studies we found that acylphosphatase from heart muscle, used at concentrations within the physiological range, actively hydrolyzes the phosphoenzyme of cardiac sarcoplasmic reticulum Ca^{2+} pump, with an apparent K_m on the order of 10^{-7} M, suggesting an high affinity of the enzyme for this special substrate. In unphosphorylated vesicles acylphosphatase enhanced the rate of ATP hydrolysis and Ca^{2+} uptake with a concomitant significant decrease in apparent K_m for Ca^{2+} and ATP. In vesicles whose phospholamban was PKA-phosphorylated, acylphosphatase also stimulated the rate of Ca^{2+} uptake and ATP hydrolysis but to a lesser extent, and the K_m values for Ca^{2+} and ATP were not significantly different with respect to those found in the absence of acylphosphatase. These findings suggest that acylphosphatase, owing to its hydrolytic effect, accelerates the turnover of the phosphoenzyme intermediate with the consequence of an enhanced activity of Ca^{2+} pump. It is known that phosphorylation of phospholamban results in an increase of the rate at which the phosphoenzyme is decomposed. Thus, as discussed, a competition between phospholamban and acylphosphatase effect on the phosphoenzyme might be proposed to explain why the stimulation induced by this enzyme is less marked in PKA-phosphorylated than in unphosphorylated heart vesicles.

Active Ca^{2+} transport across the membranes of sarcoplasmic reticulum (SR)[1] plays a central role in the excitation-contraction coupling of cardiac muscle. More specifically, this process, in concert with the activities of two sarcolemmal systems, namely the Ca^{2+}-ATPase and the Na^+/Ca^{2+} exchanger (1), is essential to promote muscle relaxation by rapidly removing Ca^{2+} from the cytosol (2, 3). As well as in skeletal muscle, the energy-dependent calcium transport into cardiac SR depends on the activity of a Ca^{2+}-dependent ATPase (EC 3.6.1.3, ATP phosphohydrolase), which functions as a Ca^{2+} pump, transducing chemical energy of ATP into osmotic work, consisting in a gradient of calcium ions across the SR membrane. In fact, Ca^{2+} translocations are tightly coupled with ATP hydrolysis, which is accomplished by SR Ca^{2+}-ATPase through a complex series of reactions involving the formation and the decomposition of a phosphoenzyme intermediate (3). As it occurs for other transport ATPase, the phosphoenzyme (*E*P) of SR Ca^{2+}-ATPase was recognized as an acylphosphate, since phosphorylation takes place at a carboxyl group of an aspartic acid residue (4, 5). A distinctive feature of cardiac SR Ca^{2+}-ATPase is its regulation by a specific membrane protein, named phospholamban, whose phosphorylation by a cAMP- or a Ca^{2+}/calmodulin-dependent protein kinase leads to an increase in the rate of active Ca^{2+} transport (6).

Acylphosphatase (EC 3.6.1.7), a widespread enzyme that is well represented in skeletal and heart muscle (7), catalyzes the hydrolysis of the carboxylphosphate bond of acylphosphates such as 3-phosphoglyceroyl phosphate (8), carbamoyl phosphate (9), and succinoyl phosphate (10). For several years we have been investigating structural and functional properties of acylphosphatase purified from muscle tissue of various animal species. More recently we have found that this enzyme, a cytosolic highly basic protein (its pI is approximately 11), in addition to the above mentioned low molecular weight soluble substrates, can hydrolyze the acylphosphorylated intermediates involved in the action mechanism of some transport ATPases, notably those of erythrocyte membrane (11) and of heart sarcolemma Ca^{2+}-ATPase (12).

In the present paper we report the results of studies that we conducted to evaluate whether a similar effect of acylphosphatase on the *E*P intermediate of heart SR Ca^{2+}-ATPase resulted in modified functional properties of this important calcium pump. Possible changes in acylphosphatase effects upon phospholamban phosphorylation were also investigated.

MATERIALS AND METHODS

Cyclic AMP-dependent protein kinase from bovine heart, 3′,5′-cyclic AMP, K^+-oxalate, and Tris-ATP were from Sigma Chemie, Milano, Italy. [γ-^{32}P]ATP (3000 Ci/mmol) and $^{45}CaCl_2$ (29.77 mCi/mg) were purchased from NEN DuPont (Brussels, Belgium). Nitrocellulose filters (0.45 μm) were obtained from Sartorius (Firenze, Italy). All other compounds were of analytical grade.

Acylphosphatase was purified to homogeneity from bovine heart according to Ramponi *et al.* (13) for the extraction and according to Stefani *et al.* (14) for the other steps. The enzyme, isolated as a pure product, had a specific activity of 3650 units/mg of protein using benzoyl phosphate as substrate (15). Benzoyl phosphate was synthesized as per Camici *et al.* (16). Cardiac sarcoplasmic reticulum vesicle (SRV) protein content was assayed by the biuret method of Beisenherz *et al.* (17) using

* This work was supported by grants from the Ministero dell' Università e della Ricerca Scientifica e Tecnologica, Fondi ex quota 60% and 40% (Progetto Nazionale Insufficienza Cardiaca) and by Telethon Grant 686. The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked "*advertisement*" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

‡ To whom correspondence should be addressed: Tel.: 39-55-413765; Fax: 39-55-4222725.

[1] The abbreviations used are: SR, sarcoplasmic reticulum; SRV, SR vesicle; *E*P, phosphoenzyme; PKA, cAMP-dependent protein kinase.

bovine serum albumin as a standard.

Preparation of Cardiac SRVs—All operations were carried out at 4 °C. Cardiac SRVs were isolated from trimmed calf ventricles according to Jones *et al.* (18) except that the Ca^{2+}-oxalate loading step was omitted. The final vesicles were stored frozen at −80 °C in 2 mM Hepes, pH 7, 0.3 M KCl, 0.3 M sucrose. In a typical preparation, a yield of 55–65 mg of vesicle protein/100 g of wet tissue was routinely obtained.

Ouabaine-sensitive Na^+,K^+-ATPase (see below) and cytochrome *c* oxidase (19) activities were measured to determine the extent of contamination of SR fraction by sarcolemma and mitochondria.

Preparation of SR Ca^{2+}-ATPase Phosphoenzyme and Measurement of Its Turnover and Decomposition Rate without and with Acylphosphatase—Phosphorylation of SRVs was carried out at 0 °C according to Beekman *et al.* (20) with slight modifications. The standard reaction mixture (total volume 1 ml) contained 30 mM Tris-HCl, pH 7, 1 mM $MgCl_2$, 120 mM KCl, 125 μM $CaCl_2$ or 3 mM EGTA, and 1 mg of cardiac SRVs. The reaction was started by the addition of 10 μM[γ-^{32}P]ATP (0.2 mCi/μmol), and after 30 s of incubation the reaction was stopped by adding 4 ml of ice-cold 6% trichloroacetic acid containing 1 mM ATP and 5 mM NaH_2P0_4. The suspension was centrifuged at 30,000 × *g* for 10 min, and the supernatant was discarded. Then the pellet was washed once with the above trichloroacetic mixture and two more times with 0.15 M Tris-HCl, pH 7.4. The final pellet was resuspended in 30 mM Tris-HCl, pH 7.4, and aliquots were assayed for radioactivity and protein content. The level of phosphoenzyme was taken as the difference between the amount of ^{32}P incorporated into vesicles in the presence of $CaCl_2$ or EGTA. Phosphorylated vesicles (1 mg/ml) were incubated in 30 mM Tris-HCl, pH 7.4, at 37 °C without and with differing amounts of acylphosphatase. After 30 s, the reaction was stopped with 1 volume of ice-cold 10% trichloroacetic acid, and the suspension was centrifuged at 13,000 × *g* for 5 min. Aliquots of the supernatant were taken to measure ^{32}P radioactivity. The release of ^{32}P from *E*P was expressed in pmol/min, since in preliminary experiments performed with variable amounts of phosphorylated vesicles we found that it proceeded linearly over 2 min. In another series of experiments, differing amounts of phosphorylated vesicles were incubated with a fixed amount of acylphosphatase (100 units). Controls for spontaneous hydrolysis were incubated under the same conditions for each concentration of phosphorylated vesicles and subtracted to give acylphosphatase-induced phosphate release. To estimate the turnover rate of *E*P, SRVs were phosphorylated at 15 °C according to Shigekawa *et al.* (21) in the absence and in the presence of varying amounts of acylphosphatase. Reactions were started by the addition of 20 μM [γ-^{32}P]ATP (0.1 mCi/μmol) and terminated after 30 s by the addition of ice-cold trichloroacetic acid (5% final concentration) containing 0.1 mM NaH_2PO4 and 1 mM ATP. After centrifugation, aliquots were taken from the supernatant and phosphate was determined as in Nassi *et al.* (22), while the pellets were treated according the above procedure (21). Both Ca^{2+}-dependent ATPase activity and Ca^{2+}-dependent phosphoenzyme level were estimated by subtracting the respective values observed with 1 mM EGTA from those obtained in the presence of Ca^{2+}.

To measure the time course of undenaturated phosphoenzyme decomposition, SRVs were phosphorylated at 15 °C in the above described conditions (21). After 30 s, a mixture of 21 mM ADP, 20.9 mM $MgCl_2$, and 145 mM EGTA (25 μl) were added to 0.5 ml of reaction medium, and the time courses of the phosphoenzyme decomposition were measured.

ATPase Activity Measurements—For Ca^{2+}-ATPase, total activity was assayed in a standard reaction mixture containing 50 mM Tris-HCl, pH 7.4, 3 mM $MgCl_2$, 100 mM KCl, 5 mM NaN_3, 50 μM $CaCl_2$, 3 mM ATP, and 50 μg/ml vesicle protein. To determine the basal ATPase activity, the assays were carried out in presence of 1 mM Tris-EGTA instead of $CaCl_2$. Reactions were started by the addition of ATP or of an aliquot of the vesicle suspension and stopped after 10 min with one volume of ice-cold 20% trichloroacetic acid. After centrifugation (12,000 rpm for 5 min), the amount of P_i released was measured according to Baykov *et al.* (23) in aliquots of the supernatant. Ca^{2+}-dependent ATPase activity was estimated by subtracting the basal ATPase activity from the total Ca^{2+}-ATPase and was expressed as nmol/min/mg of SRV protein. Routinely, in the ATPase assays with 50 μM $CaCl_2$ and no EGTA, a free Ca^{2+} concentration of approximately 10 μM was calculated using the equations of Katz *et al.* (24).

Ouabaine-sensitive Na^+,K^+-ATPase was assayed in a medium containing 50 mM Tris-HCl, pH 7.4, 3 mM $MgCl_2$, 100 mM NaCl, 5 mM NaN_3, 1 mM Tris-EGTA, 100 mM KCl, 3 mM ATP, and 50 μg/ml vesicle protein with and without 1 mM ouabain.

Ca^{2+} Influx Measurements into SRVs—For these measurements the reaction mixture was the same as for ATPase assays except that it included $^{45}CaCl_2$ (5 μCi/μmol) and 5 mM oxalate. After 30 s of incubation at 37 °C, the vesicles were separated from the medium by filtration through a Millipore filter (0.45-μm pore size), and then the filter was immediately washed two times with 4 ml of ice-cold 20 mM Tris-HCl, pH 7.4, 1 mM EGTA, and 0.1 M HCl. Oxalate-facilitated ^{45}Ca uptake was measured as the difference in ^{45}Ca influx into vesicle at zero time and at the end of incubation (30 s). Radioactivity trapped on the filter was determined by liquid scintillation spectroscopy.

Treatment of SRVs with cAMP-dependent Protein Kinase (PKA) and cAMP to Induce Phospholamban Phosphorylation—SRVs (0.5 mg/ml) were incubated in 40 mM Tris-HCl, pH 7.4, 120 mM KCl, 5 mM $MgCl_2$, 5 mM Tris-ATP with 10 μM cAMP and 1 mg/ml PKA at 25 °C for 10 min. The reaction was terminated in ice.

Aliquots were taken for assaying Ca^{2+} uptake and Ca^{2+}-dependent ATPase.

In order to evidence the phosphorylation of phospholamban, the same phosphorylation conditions were used as described above except that 0.5 mM [γ-^{32}P]ATP (10 μCi/mol), 2.5 mM Tris-EGTA, and 25 mM NaF were present according to Tada *et al.* (25). The reaction was stopped by the addition of a solution containing SDS, EDTA, and β-mercaptoethanol to give final concentrations of 2%, 0.1 mM, and 1%, respectively. After standing several min on ice, this mixture was incubated for 10 min at 37 °C in order to solubilize the vesicles. A solution of 20 mM sodium phosphate, pH 7.2, 0.1 mM EDTA, 1% β-mercaptoethanol, 10% glycerol, and 0.005% bromphenol blue was added to the mixture, and aliquots containing 40 μg of SR protein were applied to an SDS-15% polyacrylamide gel for electrophoresis according to Laemmli (26). For autoradiography, the dried gel was exposed to Kodak X-Omat AR film with an Agfa-Gevaert (Curix MR 800) intensifier screen at −80 °C for 3 days, and the film was then developed.

Data Analysis—Curves were drawn on the basis of the mean values. The data about *E*P dephosphorylation were analyzed by means of a linear regression analysis of observed values plotted in double reciprocal form.

The data concerning the dependence of ATP hydrolysis and Ca^{2+} uptake on free Ca^{2+} and ATP concentrations were analyzed using an equation for a general cooperative model for substrate as follows,

$$v = V_{max}[S]^N/(K^N_{0.5} + [S]^N) \quad \text{(Eq. 1)}$$

Where V_{max} (maximum velocity), $K_{0.5}$ (concentration required to attain half-maximal velocity; apparent K_m), and N (the equivalent of the Hill coefficient) were calculated using the Fig.P computer program by Biosoft (Cambridge, United Kingdom). Statistical analysis was performed by Student's *t* test or by one way analysis of variance.

RESULTS

Cardiac SRVs used for these studies were examined to determine the possibility that contaminating materials, derived from other cellular structures, were present in these preparations.

Sarcolemma and mitochondria contaminations were virtually absent since ouabain-sensitive Na^+,K^+-ATPase and cytochrome *c* oxidase activities were negligible.

Effect of Acylphosphatase on the Phosphorylated Intermediate of SRVs—SRVs incubated in presence of [γ-^{32}P]ATP and Ca^{2+}, as described under "Materials and Methods," formed a Ca^{2+}-dependent *E*P, whose level, after subtracting nonspecific ^{32}P bound in presence of EGTA instead of Ca^{2+}, was, on average, 145 pmol of ^{32}P bound/mg of SRV protein, a value that agrees with that reported by Beekman *et al.* (20), from whose method our procedure derives.

To see whether the rate of *E*P dephosphorylation was affected by acylphosphatase, labeled vesicles were incubated with different amounts of the enzyme, from 25 to 200 units/mg of SRV protein. Such ratios were chosen because they are within the physiological range, which, in heart muscle, was estimated to be 80–130 units/mg of SRV protein (7). As shown in Fig. 1, in the presence of acylphosphatase, the release of phosphate was always higher than spontaneous hydrolysis, even at the lowest enzyme concentration, and augmented significantly with the increase in acylphosphatase/SRV protein ratio. The maximal effect was observed with 100 units/mg of SRV protein, at which concentration the phosphate release was

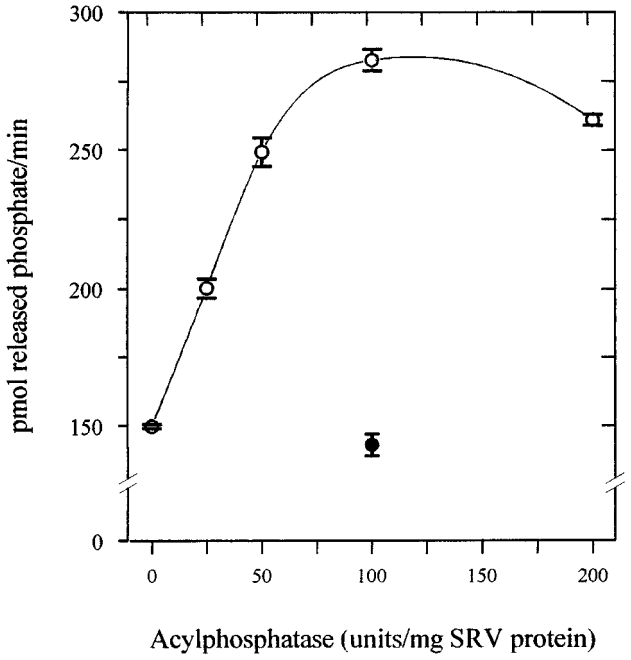

FIG. 1. **Effect of different acylphosphatase concentrations on SR Ca^{2+}-ATPase phosphoenzyme intermediate.** Labeled vesicles (1 mg) were incubated in 1 ml of 30 mM Tris-HCl, pH 7.4, at 37 °C without and with differing amounts of acylphosphatase. The phosphoenzyme level was 145 pmol of ^{32}P bound/mg of SRV protein. The initial rate of phosphate release was measured as described under "Materials and Methods" and was expressed as pmol/min. Each point is the mean ± S.E. of five experiments performed on differing vesicle preparations. All the changes in phosphate release induced by active acylphosphatase were statistically significant ($p < 0.01$ by the one-way analysis of variance). Heat-denaturated acylphosphatase (2 h at 100 °C) (●) was added at a concentration corresponding to 100 units of active enzyme/mg of SRV protein.

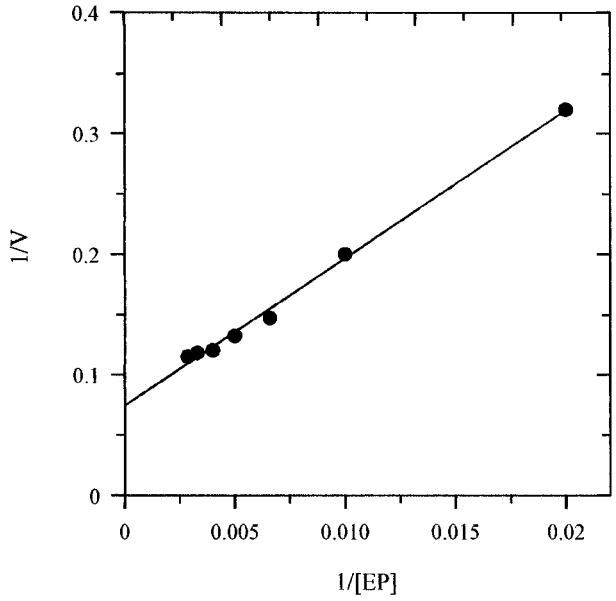

FIG. 2. **Initial rate of acylphosphatase-induced dephosphorylation of cardiac SR Ca^{2+} ATPase phosphoenzyme as a function of *E*P concentration.** 100 units of acylphosphatase were incubated in 30 mM Tris-HCl, pH 7.4, at 37 °C with differing amounts of labeled vesicles. *E*P concentration [*E*P] was expressed as pmol of ^{32}P bound per ml. The initial rate of dephosphorylation (*V*), net for spontaneous hydrolysis, was expressed as pmol of ^{32}P released per min/ml. Each point represents the mean value of five determinations. Data are shown as a double reciprocal plot.

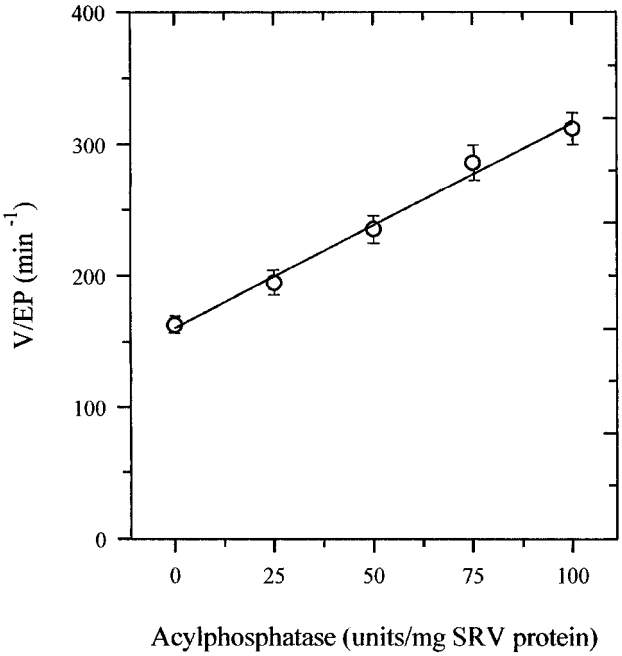

FIG. 3. **Acylphosphatase dependence of the ratio between the rate of ATP hydrolysis (*V*) and Ca^{2+}-ATPase *E*P level.** The rates of ATP hydrolysis and the Ca^{2+}-ATPase phosphoenzyme level were measured at 15 °C in a medium containing 0.25 mg/ml SRV protein, 15 mM imidazole-HCl (pH 7), 2 mM $MgCl_2$, 20 μM [γ-^{32}P]ATP, and 20 μM $CaCl_2$. Each point represents the mean value ± S.E. of five determinations. Changes observed with increasing amounts of acylphosphatase were statistically significant ($p < 0.01$ by the one way analysis of variance).

about 2-fold over spontaneous hydrolysis. No significant enhancement of phosphate release was observed using higher concentrations of the enzyme. On the other hand, heat-denaturated acylphosphatase (2 h at 100 °C) added at a concentration corresponding to 100 units/mg of SRV protein of the active enzyme did not produce significant modifications of the phosphate release with respect to spontaneous dephosphorylation.

To evaluate the affinity of acylphosphatase toward *E*P, variable amounts of phosphorylated vesicles were incubated with a fixed amount of our enzyme. Acylphosphatase-induced phosphate release rose with increasing *E*P concentrations, and from a double reciprocal plot of these data, resulting in a straight line, an apparent K_m of 157.08 ± 19.60 nM (mean ± S.E.) was calculated (Fig. 2).

Besides these studies, which were conducted using the acid-denaturated phosphoenzyme, other experiments were performed with the aim of establishing whether acylphosphatase affected the turnover rate of phosphoenzyme intermediate and had a different effect on the two *E*P forms, namely the ADP-sensitive (*E*1P) and the ADP-insensitive (*E*2P) form. According to Shigekawa and Akowitz (21), the rate of *E*P turnover was determined as the ratio between the rate of ATP hydrolysis and the phosphoenzyme levels, both being measured at the steady state, which, under our conditions, was reached within 30 s after the start of the phosphorylation reaction. As shown in Fig. 3, when these measurements were taken in the presence of differing acylphosphatase amounts, the ratio increased with acylphosphatase concentrations, reaching a value that, with 100 units/mg of SRV protein, was about 2-fold greater than that in the absence of added enzyme. To explore the possibility of a different effect of acylphosphatase on *E*1P and *E*2P, we measured the time course of the phosphoenzyme decomposition after the steady state was reached and further phosphorylation was prevented by adding an excess of EGTA and MgADP. In agreement with previous reports (21) we found that phosphoenzyme decomposition exhibited an initial rapid phase without a

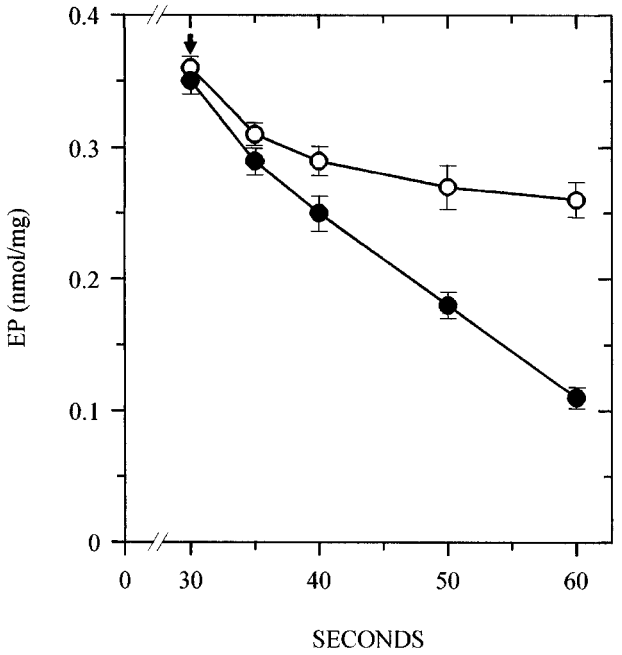

FIG. 4. **Time course of decomposition of cardiac Ca^{2+}-ATPase *E*P after the addition of 21 mM ADP, 20.9 mM $MgCl_2$, and 145 mM EGTA with (●) and without (○) acylphosphatase (100 units/mg of SRV protein).** SRVs were phosphorylated as described under "Materials and Methods." At 30 s (↓), 25 μl of a mixture of 21 mM ADP, 20.9 mM $MgCl_2$ and 145 mM EGTA were added to 0.5 ml of reaction medium, and the time courses of the phosphoenzyme decomposition were measured. Each point represents the mean value ± S.E. of five determinations.

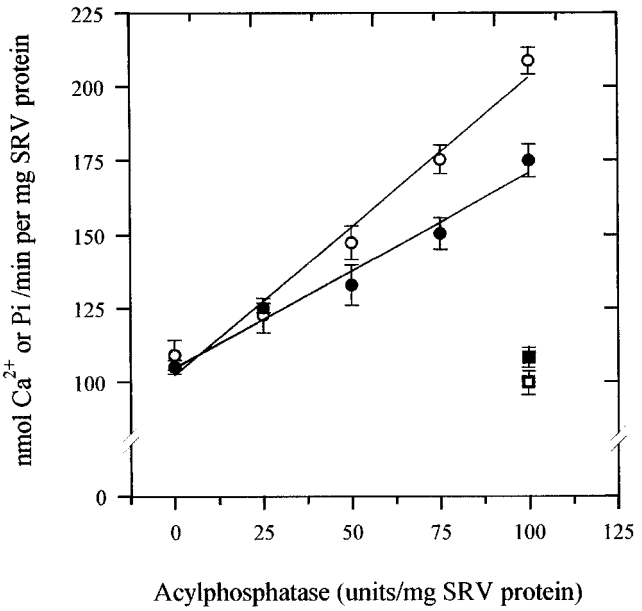

FIG. 5. **Effect of different acylphosphatase concentrations on Ca^{2+} ATPase activity and Ca^{2+} uptake of cardiac SRVs.** Ca^{2+} ATPase activity (○) and Ca^{2+} uptake (●) were assayed as described under "Materials and Methods." Ca^{2+}-ATPase activity was expressed as nmol of ATP split per min/mg of SRV protein and Ca^{2+} uptake as nmol of Ca^{2+} transported into vesicles per min/mg of SRV protein. Each point represents the mean value ± S.E. of five determinations. Changes observed in Ca^{2+}-ATPase activity and Ca^{2+} transport, with increasing amounts of acylphosphatase, were statistically significant ($p < 0.01$ by the one way analysis of variance). □ and ■, respectively, indicate the values obtained for Ca^{2+} ATPase activity and Ca^{2+} uptake with an amount of heat-denaturated acylphosphatase corresponding to 100 units of the active enzyme.

corresponding P_i liberation, followed by a slow phase, where the amount of P_i liberated corresponded to the decrease in *E*P level. The rapid phase is ascribed to the decomposition of the ADP-sensitive form of phosphoenzyme that reacts with added ADP to form ATP, whereas the slow late phase represents the hydrolysis of the ADP-insensitive phosphoenzyme that does not donate its phosphate group to ADP. As it is apparent in Fig. 4, in the presence of acylphosphatase (100 units/mg of SRV protein) the rate of the slow phase of *E*P decomposition was markedly increased when the rate of the rapid phase was slightly affected, which suggests a preferential action of our enzyme toward the ADP-insensitive form (*E*2P) of phosphoenzyme.

Effect of Acylphosphatase on the Ca^{2+}-ATPase Activity and Ca^{2+} Uptake of SRVs—The rate of Ca^{2+}-dependent ATP hydrolysis by SRVs was measured at the free Ca^{2+} concentration of 10 μM, which, in agreement with other authors (27–29), we found to represent the optimal concentration for the Ca^{2+}-dependent ATP hydrolysis. As stated above, mitochondrial contamination was negligible in our SRV preparations; however, sodium azide was present in all assays to inhibit the activity of mitochondrial Ca^{2+}-ATPase, eventually present as a minor contaminant (6). This ensured that the measured Ca^{2+}-ATPase activity was only due to SRVs. In order to compare the effects on ATP hydrolysis and on Ca^{2+} transport all these determinations were performed in the same experimental conditions except that in Ca^{2+} uptake assays oxalate was added in order to enhance the amount of transported Ca^{2+} into the vesicles, since ATPase activity was not affected by this compound (3). Thus, oxalate-facilitated Ca^{2+} uptake was measured and expressed as nmol of Ca^{2+} transported/min/mg of SRV protein. A 30-s incubation was performed in Ca^{2+} transport experiments after we found that Ca^{2+} influx measured at 30-s intervals proceeded linearly over a 2 min period. As shown in Fig. 5, in the presence of increasing amounts of acylphosphatase the rates of Ca^{2+}-dependent ATP hydrolysis and of Ca^{2+} uptake were significantly stimulated. Moreover, with all the used enzyme concentrations, the enhancements of the two processes were quantitatively similar; with 100 units/SRV protein, the concentration that in the present study gave the maximal effect on the phosphate release from *E*P, both Ca^{2+}-ATPase activity and Ca^{2+} uptake were almost doubled with respect to the values observed without added acylphosphatase. No significant effect on these processes was observed using heat-denaturated acylphosphatase.

We also studied the effect of acylphosphatase on the rate of ATP hydrolysis and of Ca^{2+} uptake as a function of free Ca^{2+} and ATP concentrations. Since a positive cooperativity was described in the Ca^{2+} dependence of calcium transport into SR, due to the presence of two Ca^{2+} binding sites in the Ca^{2+} pump (30), these data were analyzed using the Michaelis-type equation reported under "Materials and Methods," which is suitable for both cooperative and noncooperative ($n = 1$) behaviors. As illustrated in Fig. 6, acylphosphatase markedly increased ATP hydrolysis at all used free Ca^{2+} and ATP levels. Without the enzyme the calculated concentrations required for half-maximal ATPase activity (apparent K_m values) were 1.40 ± 0.21 μM for Ca^{2+} and 0.26 ± 0.04 mM for ATP, both findings in accordance with previous reports (28, 31). With acylphosphatase these values were significantly lower, notably 0.36 ± 0.06 μM for Ca^{2+} and 0.16 ± 0.02 mM for ATP. Both in the absence and in the presence of acylphosphatase, the calculated *N* values for the rate of ATP hydrolysis as a function of free Ca^{2+} and ATP concentrations were near 1, indicating the lack of positive cooperative effects.

As for the dependence of Ca^{2+} uptake on the free Ca^{2+} concentration (Fig. 7), in the absence of acylphosphatase an apparent K_m of 1.77 ± 0.23 μM and an *N* value of 1.42 ± 0.20 were calculated; when the enzyme was added, also in this case

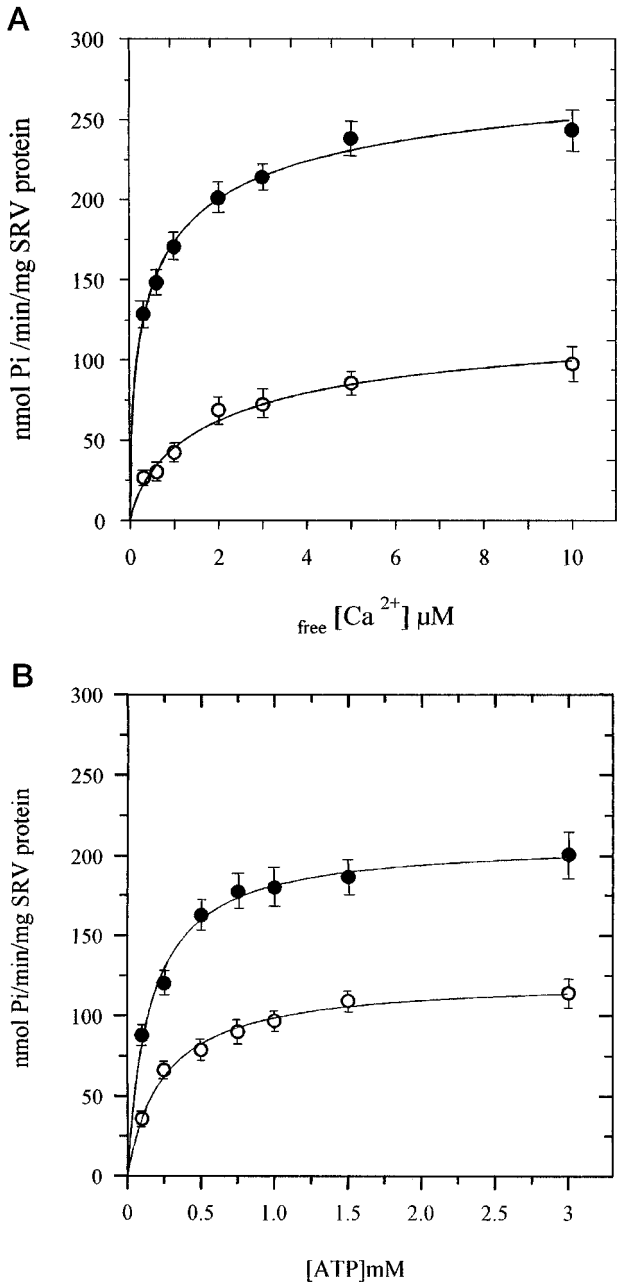

FIG. 6. **Cardiac SR Ca^{2+} ATPase activity as a function of free Ca^{2+} (*A*) and ATP (*B*) concentrations.** SRVs (50 μg/ml) were assayed in the absence (○) and in the presence (●) of 100 units of acylphosphatase. Each point represents the mean value ± S.E. of five determinations.

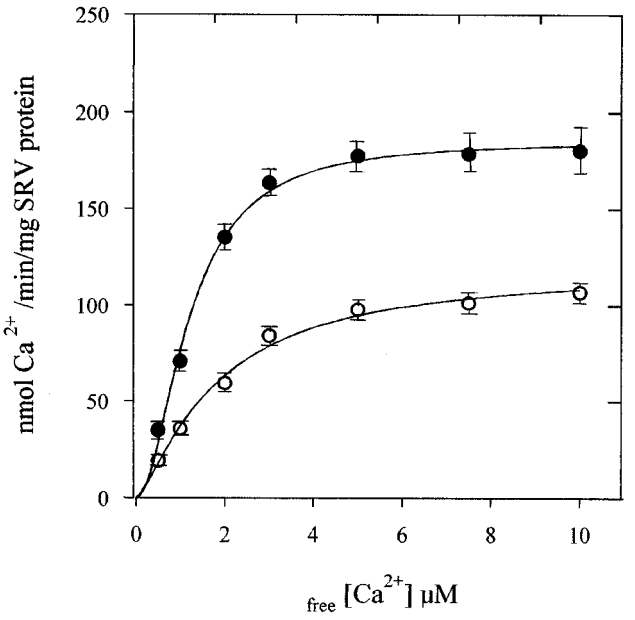

FIG. 7. **Cardiac SR Ca^{2+} uptake as a function of free Ca^{2+} concentration.** SRVs (50 μg/ml) were assayed in the absence (○) and in the presence (●) of 100 units of acylphosphatase. Each point represents the mean value ± S.E. of five determinations.

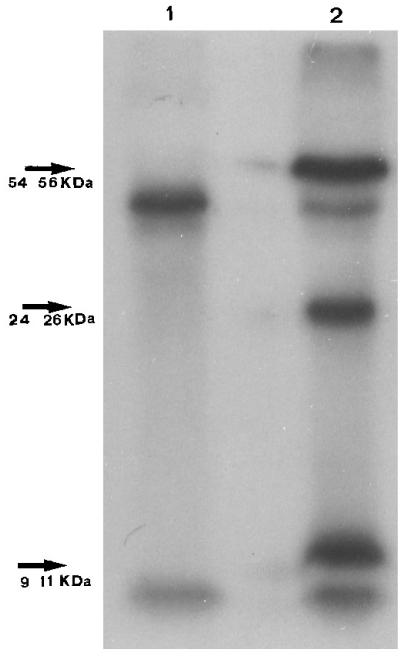

FIG. 8. **Autoradiogram of PKA-phosphorylated SRVs.** SRVs were phosphorylated as described under "Materials and Methods" in the absence (*lane 1*) and in the presence (*lane 2*) of PKA and cAMP. Molecular mass markers are shown on *left*.

at 100 units/mg of SRV protein, an increase in the rate of Ca^{2+} transport was observed at all the used free Ca^{2+} concentrations, and the apparent K_m value was significantly lowered to 1.21 ± 0.08 μM, while the value of N was not significantly changed.

Autoradiogram of SRVs Phosphorylated by PKA and cAMP—SRVs were phosphorylated with [γ-^{32}P]ATP in the presence of PKA and cAMP as described under "Materials and Methods." Fig. 8 shows the autoradiography of ^{32}P-phosphorylated SRVs subjected to electrophoresis. Phosphorylation performed in the presence of PKA and cAMP resulted in a band at about 26–28 kDa corresponding to the phosphorylated phospholamban and another one at 9–11 kDa, probably a low molecular mass form of this protein (32). It is also evident that a band at about 54–56 kDa likely derived from autophosphorylation of protein kinase occurring at the catalytic subunit as reported by other authors (25). These bands were not present when SRVs were phosphorylated in the absence of PKA and cAMP.

Effect of Acylphosphatase on the Ca^{2+}-ATPase Activity and on the Ca^{2+} Uptake in SRVs Phosphorylated by PKA and cAMP—For these studies SRVs were treated as described under "Materials and Methods." Phosphorylated SRVs showed, as previously reported (3, 6, 30, 33, 34), a marked stimulation of Ca^{2+}-dependent ATPase activity and Ca^{2+} uptake. When we measured the rate of ATP hydrolysis as a function of the free Ca^{2+} and ATP concentrations (Fig. 9), we found that in the phosphorylated SRVs the calculated apparent K_m values were

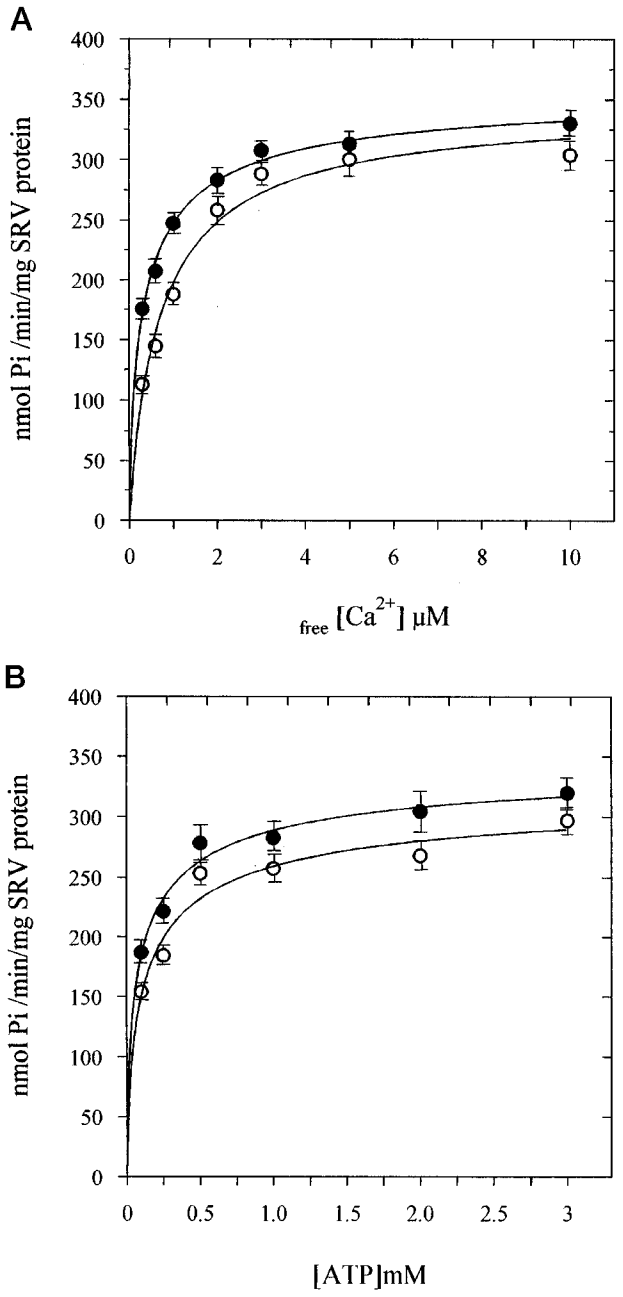

FIG. 9. **Ca^{2+} ATPase activity of PKA-phosphorylated SRVs as a function of free Ca^{2+} (*A*) and ATP (*B*) concentrations.** SRVs were phosphorylated as described under "Materials and Methods," and aliquots were taken and assayed for Ca^{2+} ATPase activity in the standard reaction medium in the absence (○) and in the presence (●) of 100 units of acylphosphatase. Each point represents the mean value ± S.E. of five determinations.

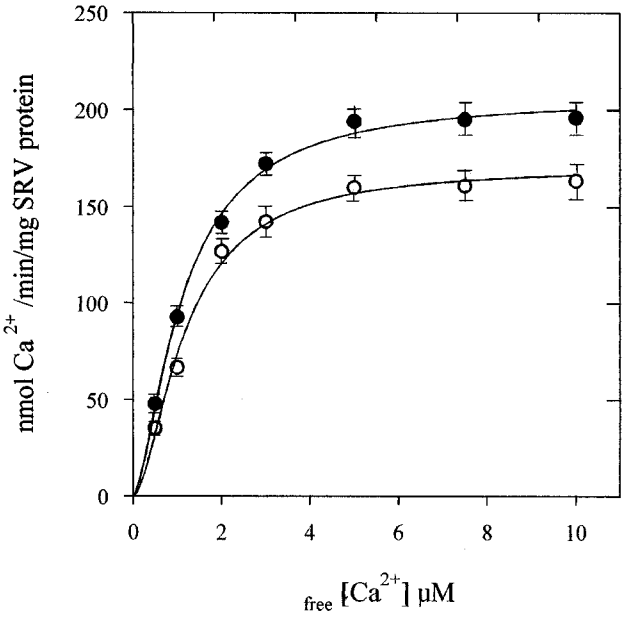

FIG. 10. **Ca^{2+} uptake of PKA phosphorylated SRVs as a function of free Ca^{2+} concentration.** SRVs were phosphorylated as described under "Materials and Methods," and aliquots were taken and assayed for Ca^{2+} uptake in the standard reaction medium in the absence (○) and in the presence (●) of 100 units of acylphosphatase. Each point represents the mean value ± S.E. of five determinations.

0.69 ± 0.09 μM for Ca^{2+} and 0.11 ± 0.02 mM for ATP, both values significantly lower than those observed in unphosphorylated vesicles ($p < 0.01$). As for the kinetics of Ca^{2+} transport (Fig. 10), phosphorylation resulted, as expected, in a reduction of the free Ca^{2+} concentration required for half-maximal Ca^{2+} uptake (1.17 ± 0.08 μM versus 1.77 ± 0.23 μM); in this connection, in contrast with previous reports (30) but in agreement with Movsesian (35), we did not find significant changes in the positive cooperativity for Ca^{2+} according to whether phospholamban was in its dephospho- or phospho-form. When acylphosphatase was added to the phosphorylated SRVs, always at the optimal concentration of 100 units/mg of SRV protein, the rates of both ATP hydrolysis and Ca^{2+} transport were further and significantly augmented, but the stimulatory effects of our enzyme were less striking (only about 20% over the control values) than those observed using unphosphorylated vesicles. Also the changes induced by acylphosphatase in the apparent K_m values for Ca^{2+} and ATP, both for ATPase activity and Ca^{2+} uptake, were less marked in the phosphorylated vesicles.

Table I summarizes all the observed acylphosphatase effects on the kinetic parameters of the Ca^{2+} pump ATPase in phosphorylated and unphosphorylated heart SRVs.

DISCUSSION

The findings here reported indicate that acylphosphatase can actively hydrolyze the phosphoenzyme intermediate of the cardiac SR Ca^{2+} pump. Such result was expected, given the acylphosphate nature of the phosphoenzyme, the catalytic properties of acylphosphatase, and our previous findings indicating a similar effect of our enzyme on the *E*P intermediates of other Ca^{2+}-ATPase. However, we think that two features of acylphosphatase action emerging from the present study are of interest: one is that the hydrolysis of *E*P occurred to a significant extent even using an enzyme amount corresponding to the lower limit of the physiological content in heart muscle; the other is represented by the low K_m value (on the order of 10^{-7} M) that we found for *E*P hydrolysis, which suggests a distinctly high affinity in our enzyme toward this particular substrate, since the K_m values for other potential substrates, such as the soluble low molecular weight compounds mentioned in the Introduction, are always higher than 10^{-4} M.

When added to intact SRVs, used as a source of the Ca^{2+} pump as it exists *in situ*, acylphosphatase affected the functional properties of this active transport system, notably the kinetics of ATP hydrolysis and of Ca^{2+} transport. In order to compare the effects on the two processes all the experiments were performed under the same conditions of temperature, pH, and Ca^{2+} and ATP concentrations. Acylphosphatase addition, at the same concentrations used to study the effects on *E*P, resulted in a stimulation of the rate of ATP hydrolysis that

TABLE I
Effect of acylphosphatase on Ca^{2+}-ATPase activity and Ca^{2+} uptake in unphosphorylated and in PKA-phosphorylated cardiac SRVs

	Unphosphorylated SRVs					Phosphorylated SRVs				
	Ca^{2+}-ATPase			Ca^{2+}		Ca^{2+}-ATPase			Ca^{2+}	
	Activity	K_mCa^{2+}	K_m ATP	Uptake	K_mCa^{2+}	Activity	K_mCa^{2+}	K_m ATP	Uptake	K_mCa^{2+}
	nmol/mg/min	*μM*	*mM*	*nmol/mg/min*	*μM*	*nmol/mg/min*	*μM*	*mM*	*nmol/mg/min*	*μM*
Control	109.04 ± 5.03	1.40 ± 0.21	0.26 ± 0.04	105.05 ± 2.31	1.77 ± 0.23	296.20 ± 8.94	0.69 ± 0.09	0.11 ± 0.02	163.60 ± 6.62	1.17 ± 0.08
ACPase	208.70 ± 4.57[a]	0.36 ± 0.06[b]	0.16 ± 0.02[b]	174.60 ± 5.81[a]	1.21 ± 0.08[b]	346.10 ± 9.35[a]	0.31 ± 0.03[b]	0.08 ± 0.01[c]	192.80 ± 6.88[a]	1.14 ± 0.08[c]

[a] $p < 0.02$ when compared with control values using Student's t test ($n = 5$).
[b] $p < 0.05$ when compared with control values using Student's t test ($n = 7$).
[c] Not significant.

matched a parallel enhancement of ATP-dependent Ca^{2+} influx into SRVs. Thus, although the effects were more marked with increasing acylphosphatase concentrations, no remarkable changes were observed in the stoichiometric Ca^{2+}/ATP ratio, which, in agreement with several previous reports (37, 38) was always near the value of 1 mol of Ca^{2+} transported per mol of ATP hydrolyzed. Apropos of these results, it should be noted that acylphosphatase does not exhibit *per se* hydrolytic activity on ATP, nor did its addition induce changes in the ATP-independent Ca^{2+} influx into SRVs (data not shown); thus, the increase in the rate of ATP hydrolysis may only be ascribed to a stimulation of the Ca^{2+} pump ATPase activity, while the enhancement of Ca^{2+} transport is not the result of a change in the passive permeability of SR membrane to this cation. It is also noteworthy that heat-denaturated acylphosphatase (2 h at 100 °C), which did not affect the phosphate release from *E*P, also did not modify ATPase and Ca^{2+} pumping activities, indicating that all the observed acylphosphatase effects require the enzyme in a catalytically active form and/or in its native conformation. This also suggests a connection between the acylphosphatase effects on *E*P hydrolysis and on the functional properties of cardiac SR pump, all the more so that, in both cases, the modifications induced by acylphosphatase were of the same sign (stimulatory) and of the same order of magnitude.

As an interpretation of the data here reported, we propose that all the observed acylphosphatase effects are the results of an accelerated *E*P turnover, which, however, would not alter the normal ordered sequence of reactions and conformational transitions associated with Ca^{2+} transport. In other words, acylphosphatase-induced hydrolysis of *E*P, in competition with its own hydrolytic catalysis, would take place on the *E*2P form, that is at step V of the reaction system here proposed and derived from that reported by Tada *et al.* (3) (Fig. 11). Since *E*2P hydrolysis is considered to be the rate-limiting step of the entire process (21), this would result in a more rapid pumping cycle and, at the same time, could favor a shift of the equilibrium between the two proposed conformationally distinctive forms of the Ca^{2+} pump, E_1 and E_2, toward E_1, characterized by higher affinity for Ca^{2+} and ATP. The results of the present study provide direct and indirect evidence in support of this interpretation. Direct evidence consists of the increased *E*P turnover rate that we observed in the presence of increasing acylphosphatase concentrations and in the finding that the hydrolytic effect of our enzyme was much more marked toward the ADP-insensitive form (*E*2P) than toward the ADP-sensitive form (*E*1P) of the phosphoenzyme intermediate. Indirect evidence comes from the observations that the effects of PKA phospholamban phosphorylation on the measured kinetic properties of heart SR Ca^{2+} pump were qualitatively and quantitatively similar to those induced by acylphosphatase. Since from the extensive studies of Tada *et al.* (3) phospholamban phosphorylation appears to cause the above effects enhancing both formation and decomposition of *E*P (39), it may be reasonable to suppose that acylphosphatase, in spite of a different kind of action, does affect in a similar way the function of the Ca^{2+} pump.

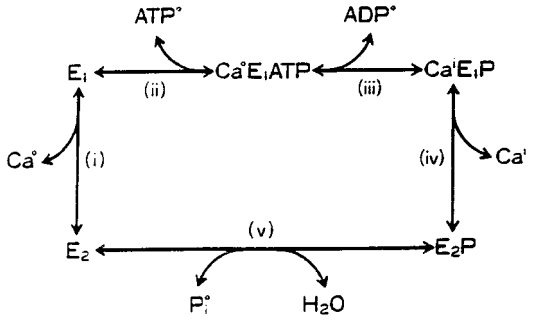

FIG. 11. **A scheme of Ca^{2+} pump ATPase.** The scheme is based on that reported by Tada *et al.* (3). E_1 and E_2 represent two different forms of the enzyme, which exhibit higher and lower affinities for Ca^{2+}, respectively; *i* and *o* indicate the inside and outside of SR membranes. E_1P is the form of the phosphorylated intermediate having higher affinity for Ca^{2+}, while E_2P has a lower affinity for Ca^{2+}.

As for the reduction in the stimulatory effect of acylphosphatase on SR Ca^{2+} pump upon phospholamban phosphorylation, it is difficult to explain this finding on the grounds of the data still now available. However, since it is generally accepted that unphosphorylated phospholamban inhibits the Ca^{2+} pump while phospholamban phosphorylation results in a relief of this inhibitory effect (40) we suggest as a tentative hypothesis that in the unphosphorylated SRVs acylphosphatase, in addition to the stimulatory effect due to its catalytic activity, could also act through another mechanism consisting of the removal of phospholamban inhibition. In fact, the basic character of acylphosphatase might favor the interaction of this enzyme protein with the Ca^{2+} pump, which exhibits affinity for polycationic compounds (37). Furthermore, studies from our laboratory (41) on the tridimensional structure of muscle acylphosphatase have shown that this protein contains a structural motif where 12 residues (from position 55 to 66) may be proposed to form an amphipatic α-helical structure with a prevalence of basic groups, a structure resembling that of the phospholamban cytoplasmic 1A domain (42), which appears to be essential for the association of phospholamban with the SR Ca^{2+} pump. Given this structural analogy, acylphosphatase might be supposed to interact with SR Ca^{2+} pump, taking the place of unphosphorylated phospholamban, whose inhibitory effect would therefore be removed. However, phospholamban does not appear to be strictly necessary for acylphosphatase action, since we found (data not shown) that this enzyme had a stimulatory effect on Ca^{2+}-ATPase activity and on Ca^{2+} transport also in SRVs from fast twitch skeletal muscle (rabbit adductor magnus), which lacks phospholamban. In any case, more conclusive proofs to establish if the acylphosphatase effect on cardiac SR Ca^{2+} pump is due, at least in part, to a displacement of phospholamban will arise from studies in pro-

gress in our laboratory; planned experiments involve the use of purified heart SR Ca^{2+}-ATPase (SERCA 2) and of a negative dominant of acylphosphatase, obtained by site-directed mutagenesis (43), which is virtually devoid of catalytic activity but retains the structural motif supposed to interact with the Ca^{2+} pump instead of phospholamban.

In conclusion, the results of the present study indicate that acylphosphatase, in its catalytically active form, can interfere with the action mechanism of heart SR Ca^{2+}-ATPase, at the same time affecting the functional properties of this active transport system. To our knowledge, this represents the first report concerning changes in the activity of heart SR Ca^{2+} pump by a cytosolic enzyme normally present in the same tissue. Certainly, at present we are not able to ascribe a physiological significance to these findings; however from some features of acylphosphatase action (notably its high affinity for *E*P and its ability to act even at low concentrations) such a hypothesis should be considered, in our opinion, something more than mere speculation. In any case, further studies about the details of acylphosphatase action and the molecular basis of its interaction with SR membrane would be of interest to ascertain if this enzyme may be involved *in vivo*, in addition to the other mechanisms now recognized, in the regulation of SR Ca^{2+} pump activity, hence in the control of calcium homeostasis in heart muscle.

Acknowledgment—We are grateful to Dr. Giovanni Rizzuti for assistance.

REFERENCES

1. Caroni, P. and Carafoli, E. (1983) *Eur. J. Biochem.* **132,** 451–460
2. Inesi G. (1985) *Annu. Rev. Physiol.* **47,** 573–601
3. Tada, M., Kadoma, M., Inui, M., and Fujii, J-I. (1988) *Methods Enzymol.* **157,** 107–154
4. Martonosi, A. (1969) *J. Biol. Chem.* **244,** 613–620
5. Bastide, F., Meissner, G., Fleischer, S., and Post, R. L. (1973) *J. Biol. Chem.* **248,** 8485–8391
6. Tada, M., Kirchberger, A., Repke, D. I., and Katz, A. M. (1974) *J. Biol. Chem.* **249,** 6174–6180
7. Berti, A., Degl'Innocenti, D., Stefani, M., Liguri, G., and Ramponi, G. (1987) *Ital. J. Biochem* **36,** 82–91
8. Ramponi, G., Treves, C., and Guerritore, A. (1967) *Experientia* (*Basel*) **23,** 1019
9. Ramponi, G., Melani, F., and Guerritore, A. (1961) *G. Biochim.* **10,** 189–196
10. Berti, A., Stefani, M., Liguri, G., Camici, G., Manao, G., and Ramponi, G. (1977) *Ital. J. Biochem.* **26,** 377–378
11. Nassi, P., Nediani, C., Liguri, G., Taddei, N., and Ramponi, G. (1991) *J. Biol. Chem.* **266,** 10867–10871
12. Nediani, C., Marchetti, E., Liguri, G., and Nassi, P. (1992) *Biochem. Int.* **26,** 715–723
13. Ramponi, G., Guerritore, A., Treves, C., Nassi, P., and Baccari, V. (1969) *Arch. Biochem Biophys.***130,** 362–369
14. Stefani, M., Camici, G., Manao, G., Cappugi, G., Liguri, G., Degl' Innocenti, D., Landi, N., and Berti, A. (1985) *Ital. J. Biochem.* **34,** 94–108
15. Ramponi, G., Treves, C., and Guerritore, A. (1966) *Experientia* (*Basel*) **22,** 705
16. Camici, G., Manao, G., Cappugi, G., and Ramponi, G. (1976) *Experientia* (*Basel*) **32,** 535–536
17. Beisenherz, G., Boltze, H. G., Bücher, T. H., Czock, R., Garbade, K. H., Meyer-Arendt, E., and Pfliderer, G. (1953) *Z. Naturforsch.* **8b,** 555–577
18. Jones, L. R., Besch, H. R., Jr., Fleming, J. W., McConnaughey, M. M., and Watanabe, A. M. (1979) *J. Biol. Chem.* **254,** 530–539
19. Remacle, J. A., Houbion, A., and Houben, A. (1980) *Biochim. Biophys. Acta* **630,** 57–70
20. Beekman, R. E., van Hardeveld, C., and Simonides, W. S. (1989) *Biochem. J.* **259,** 229–236
21. Shigekawa, M., and Akowitz, A. A. (1979) *J. Biol. Chem.* **254,** 4726–4730
22. Nassi, P., Marchetti, E., Nediani, C., Liguri, G., and Ramponi, G. (1993) *Biochim. Biophys. Acta* **1147,** 19–26
23. Baykov, A. A., Evtushenko, O. A., and Avaeva, S. M. (1988) *Anal. Biochem.* **171,** 266–270
24. Katz, A. M., Repke, D. I., Upshaw, J. E., and Polascik, M. A. (1970) *Biochim. Biophys. Acta* **205,** 473–490
25. Tada, M., Kirchberger, M. A., and Katz, A. M. (1975) *J. Biol. Chem.* **250,** 2640–2647
26. Laemmli, U. K. (1970) *Nature* **227,** 680–685
27. Wuytack, F., De Schutter, G., and Casteels, R. (1980) *Biochem. J.* **190,** 827–831
28. Shigekawa, M., Finegan, J. M., and Katz, A. M. (1976) *J. Biol. Chem.* **251,** 6894–6900
29. Gupta, R. C., Davis, B. A., and Kranias, E. G. (1988) *Membr. Biochem.* **7,** 73–86
30. Hicks, M. J., Shigekawa, M., and Katz, A. M. (1979) *Circ. Res.* **44,** 384–391
31. Sasaki, T., Inui, M., Kimura, Y., Kuzuya, T., and Tada, M. (1992) *J. Biol. Chem.* **267,** 1674–1679
32. Plank, B., Wyskovsky, W., Hellman, G., and Suko, J. (1983) *Biochim. Biophys. Acta* **732,** 99–109
33. Kirchberger, M. A., Tada, M., and Katz, A. M. (1974) *J. Biol. Chem.* **249,** 6166–6173
34. Tada, M., Ohmori, F., Yamada, M., and Abe, H. (1979) *J. Biol. Chem.* **254,** 319–326
35. Movsesian, M. A. (1992) *Basic Res. Cardiol.* **87,** 92–102
36. Deleted in proof
37. Xu, Z-C., and Kirchberger, A. M. (1989) *J. Biol. Chem.* **264,** 16644–16651
38. Chamberlain, B. K., Levitsky, D. O., and Fleischer, S. (1983) *J. Biol. Chem.* **258,** 6602–6609
39. Tada, M., and Katz, A. M. (1982) *Ann. Rev. Physiol.* **44,** 401–442
40. Lu, Y-Z., Xu, Z-C., and Kirchberger, A. M. (1993) *Biochemistry* **32,** 3105–3111
41. Pastore, A., Saudek, V., Ramponi, G., and Williams, R. J. P (1992) *J. Mol. Biol.* **224,** 427–440
42. Toyofuku, T., Kurzydlowsky, K., Tada, M., and MacLennan, D. H. (1994) *J. Biol. Chem.* **269,** 3088–3094
43. Taddei, N., Stefani, M., Magherini, F., Chiti, F., Modesti, A., Raugei, G., and Ramponi, G. (1996) *Biochemistry* **35,** 7077–7083