Introduction

The phosphoryl transfer reaction catalyzed by the Ca²⁺-transport ATPase of the sarcoplasmic reticulum is a reversible process involving the MgATP complex and the ligand free ADP anion as substrates of the forward and backward reaction respectively [1]. Mg²⁺ and Ca²⁺-ions are activators of the enzyme which performs transmembrane Ca²⁺ transport [2-4].

It has been demonstrated [5] that the above mentioned substrates and activators react with the enzyme in a distinct order, i.e. phosphorylation of the sarcoplasmic reticulum ATPase requires sequential activation by one Mg²⁺-ion and two Ca²⁺-ions [5-7] before the enzyme combines with the substrate of the forward reaction (MgATP). Regarding the backward reaction the activation by Mg²⁺ is a condition for the transfer of the enzyme's phosphoryl group to ADP. Because of its complete reversibility the activity of this reaction sequence can be measured as the exchange of γ-phosphate between ATP and ADP [4, 8].

A number of substances which inhibits the activity of the sarcoplasmic reticulum transport ATPase were identified in the past [9, 10]. Most of them, however, proved to be unsuited for the analysis of the reaction mechanism because of their relatively low inhibitory effect or of their undefined mode of inhibition. Several potent pharmacological inhibitors were revealed by a recent comprehensive screening [11]. Using some of these inhibitors (Benzoctamine, DIO 9, AMP-PNP) in this paper the sequence of the reaction steps between the sarcoplasmic transport enzyme and its activators and substrates could further be supported. Furthermore the enzyme intermediates representing the target of inhibition could be identified. A preliminary report of a part of this work has been published [12].

Materials and Methods

Preparation of sarcoplasmic reticulum

Sarcoplasmic reticulum vesicles from rabbit skeletal muscle were prepared according to Hasselbach and Makinose [13]; the protein concentration was measured by the Biuret or Kjeldahl method.

ATP-ADP Phosphate exchange activity

The compositions of the reaction mixtures are described in legends of the figures. In order to set the

---

W. Boll and M. Makinose
Max-Planck-Institut für Medizinische Forschung, Abteilung Physiologie, Jahnstraße 29, 6900 Heidelberg, Bundesrepublik Deutschland

Z. Naturforsch. 38c, 282-289 (1983); received December 3, 1982

Sarcoplasmic Transport ATPase, Enzymes Intermediates

1. Based on a detailed reaction scheme of the phosphorylation process of the sarcoplasmic transport ATPase the inhibition mechanisms of benzoctamine, DIO 9, AMP-PNP and of Ca²⁺-ions at relatively high concentrations (1 ~ 100 μM) were determined.

2. The inhibition mechanisms were analyzed by measuring the γ-phosphate exchange between ATP and ADP and evaluated by applying conventional and an extended Dixon plot procedures.

3. The kinetic patterns of the inhibition were shown to be compatible with the assumed reaction scheme.

4. Each inhibitor combines with definite intermediates: Benzoctamine with the intermediate species MgE and MgE-ATP; AMP-PNP with MgE ~ P; DIO 9 with E and MgE and Ca²⁺ at relatively high concentrations with E.

5. The central intermediate blocked by benzoctamine can partially exist as MgE-ADP-benzoc-tamine which is detected as phosphoprotein after acid denaturation.
concentration of ionic components to desired values the amounts of the substances to be added into the reaction mixture were calculated using the stability constants listed in Table I.

In every assay the concentration of Ca-EGTA or Ca-HEDTA complexes were set at 0.5 mM so that Ca$^{2+}$ concentration in assay was stabilized throughout the reaction time. The pH-value of the reaction mixtures containing 20 mM Histidine (pH 7.0) was readjusted immediately before the addition of sarcoplasmic reticulum vesicles.

The ATP-ADP-exchange reaction was started by addition of a mixture of [$\gamma$-$^{32}$P]ATP-ADP to the assay, in which the sarcoplasmic reticulum vesicles had been preincubated with the test agent for 5 min.

At desired reaction time 1 ml assay was added to 0.2 ml 0.6% Tannin-solution, and 20 µl of this mixture was transferred on a Polygram$^R$-plate (CEL 300 PEI/UV) and developed with 0.75 M KH$_2$PO$_4$ (+ 10 mM EDTA, pH 4.2). ATP- and ADP-spot were localized with UV-light, cutted out and counted in a liquid scintillation counter (Packard 3000). The amount of exchanged $\gamma$-phosphate was calculated as described previously [8].

Phosphoprotein formation

The reaction was started by addition of sarcoplasmic reticulum vesicles (0.5 mg protein/ml) and stopped after 15 sec by mixing 4 ml of the incubation medium with 16 ml of a solution containing 0.125 M perchloric acid, 1 mM unlabelled ATP and 1 mM H$_3$PO$_4$. After 15 min on ice the denaturated protein was separated by centrifugation. The pellet was washed five times with a solution (5 °C) containing 0.1 M perchloric acid and 0.2 M Na$_2$SO$_4$ and repeatedly recovered by centrifugation. The last pellet was liquefied with 1 ml Hyamine$^R$ and 0.2 ml water at 60 °C and its radioactivity counted in a liquid scintillation counter.

Results and Discussion

Several reaction schemes for the sarcoplasmic Ca$^{2+}$ transport ATPase were proposed based on various kinetic approaches [16–19]. Recently, the following reaction sequence has been ascertained by analysing the ATP-ADP exchange activity of the enzyme [5].

\[
\begin{align*}
E & \overset{K_a}{\underset{K_e}{\longleftrightarrow}} MgE \overset{K_b}{\underset{K_c}{\longleftrightarrow}} MgE \overset{K_d}{\underset{K_e}{\longleftrightarrow}} MgE \overset{K_f}{\underset{K_g}{\longleftrightarrow}} MgE-ATP \\
\text{ADP} & \overset{K_d}{\underset{K_{d'}}{\longrightarrow}} CaE \overset{P}{\underset{K_{d'1}}{\longrightarrow}} MgE \overset{P}{\underset{K_{d'2}}{\longrightarrow}} MgE-ATP \\
\text{velocity of } \gamma\text{-phosphate exchange;}
\end{align*}
\]

According to this scheme the dependence of the velocity of the $\gamma$-phosphate exchange reaction on the various reactants is given:

\[
V_A = \frac{K_A K_B K_C}{[Mg][Ca][MgATP]} + \frac{K_B K_C}{[MgATP]} [Ca] + \frac{K_D K_E}{[ADP][Mg]} [ADP]
\]

(2)

It should be noticed that each term on the right side of Eq. (2) represents the relative concentrations of the respective enzyme intermediates as they appear in Eq. (1). If an inhibitor binds to an enzyme intermediate, for example MgE, and forms an inactive intermediate species MgEI, the relative size of the native (U) and of the inactivated species (Ul) is given by

\[
UI = \frac{I_x}{K_1}
\]

(3)
where $K_i$ is the equilibrium constant for the binding reaction of the inhibitor. Then

$$UI = I \frac{1}{K_i} \frac{K_B K_C}{[Ca]^2[MgATP]}.$$  

(4)

Thus, in the presence of an inhibitor (I) Eq. (2) is extended by an additional term (UI).

Eq. (4) shows that, if an inhibitor blocks the enzyme species MgE, the relative size of the blocked species (UI) depends on $[Ca]^2$ and $[MgATP]$ like (U). If another inhibitor combines with another intermediate, the relative size of the complex UI should show a different dependence on the ligand concentration. Since the factor $UI/K_i$ represents the slope of the Dixon plot ($V_A^1$ versus [I], Eq. (4)) the intermediate which is blocked by the inhibitor can be identified from the effect which varied ligand concentrations exert on the slope of the lines in the Dixon plot [4].

Fig. 1a–d show the effect of benzoctamine on the ATP-ADP-exchange activity plotted according to Dixon. The slopes of these plots neither depend on the concentration of $Ca^{2+}$ or $Mg^{2+}$ nor on ADP yet the MgATP concentration definitely affects the slope. In Eq. (2) there is only one term which involves MgATP but not $Mg^{2+}$, $Ca^{2+}$ or ADP. This term corresponds to the intermediate $MgE$ in Eq. (1). Consequently one can conclude that this species is converted into an inhibited form by binding benzoctamine. Yet it remains uncertain whether benzoctamine blocks in addition to $MgE$ its complex with MgATP, $MgE$-ATP. The results shown in Fig. 1 establish an essential point of the reaction sequence mentioned above (Eq. (1)), namely MgATP reacts

---

**Fig. 1.** Dixon-plots of the ATP-ADP-exchange activity with benzoctamine as inhibitor. Ordinate: Reciprocal rate of ATP-ADP-exchange. Abscissa: Concentration of benzoctamine. 20 mM Histidine-buffer (pH 7.0), 0.02–0.05 mg prot/ml assay, $\mu = 0.1$, 20 $^\circ$C. a) With 0.1 or 1.0 mM $Mg^{2+}$. 3 mM MgATP, 1 mM ADP, 8 $\mu$M $Ca^{2+}$ (EGTA-buffer). b) With 0.4 or 1.0 $\mu$M $Ca^{2+}$ (HEDTA-buffer). 3 mM MgATP, 1 mM ADP, 0.5 mM $Mg^{2+}$. c) With 0.88 or 4.4 mM MgATP, 1 mM ADP, 1 mM $Mg^{2+}$, 8 $\mu$M $Ca^{2+}$ (EGTA-buffer). d) With 0.48 or 2.5 mM ADP, 1.76 mM MgATP, 1 mM $Mg^{2+}$, 8 $\mu$M $Ca^{2+}$ (EGTA-buffer).
with the enzyme after the binding of Mg\(^{2+}\) and Ca\(^{2+}\) to the enzyme.

In the presence of the inhibitor AMP-PNP the slope of the Dixon plot of the ATP-ADP-exchange activity shows no dependence on Ca\(^{2+}\) or Mg\(^{2+}\) concentration as observed with benzoctamine. Although AMP-PNP is considered to be an ATP-analogue the slope of the Dixon plot depends on the ADP concentration but not on the MgATP concentration (Fig. 2c, d) indicating that this inhibitor blocks Ca\(^{2+}\)-E~P. Again it is impossible to exclude an additional inhibition of the central intermediate Mg\(^{2+}\)-E-ATP by AMP-PNP.

The described ambiguity can be resolved by plotting the values \(V^{-1} \times [\text{MgATP}]\) (in the case of benzoctamine) or \(V^{-1} \times [\text{ADP}]\) (in the case of AMP-PNP) versus the inhibitor concentration ([I]) (Fig. 3a, b). If the central complex (Mg\(^{2+}\)-E-ATP) of the reaction and the species Mg\(^{2+}\)-E were both blocked by benzoctamine the slope \(q\) of this plot can be formulated as follows:

\[
q = \frac{K_C [\text{MgATP}]}{K_1} \cdot \frac{1}{V_{\text{max}}}
\]

where \(K_1\) is the equilibrium constant of the inhibitor's reaction with the central complex. In other words the slope of this plot should depend positively on [MgATP]. Fig. 3a shows that this indeed is the case. If benzoctamine did not block the central complex but only the Mg\(^{2+}\)-E complex,\n
\[
q = \frac{K_C}{K_1} \cdot \frac{1}{V_{\text{max}}}
\]

\(q\) should be independent of [MgATP] and constant.
phosphoprotein. Presumably the central complex in Eq. (1) involves an ADP-binding intermediate \( C_{\text{MgE}}^2 \text{E} \sim \text{P} \) which is detectable as phosphoenzyme together with other phosphorylated species. If AMP-PNP binds to \( C_{\text{MgE}}^2 \text{E} \sim \text{P} \) competing with ADP for the same binding site the consecutive formation of the \( C_{\text{MgE}}^2 \text{E} \sim \text{AMP-PNP} \) intermediate should lead to the increase of phosphoprotein formation observed (Fig. 4b).

Using DIO 9 as inhibitor the slopes of the Dixon plots become steeper when the concentrations of Mg\(^{2+}\), Ca\(^{2+}\) or MgATP are reduced [12]. In contrast the slopes proved to be independent of the ADP concentration. This means that the ADP

Regarding AMP-PNP the same procedure can be applied (Fig. 3b). Since the slope of this plot is independent of the ADP concentration one must assume that AMP-PNP solely binds to the intermediate \( C_{\text{MgE}}^2 \text{E} \sim \text{P} \), presumably in competition with ADP.

Fig. 4a and b show that the level of phosphoprotein formation of the sarcoplasmic reticulum transport ATPase is increased by the addition of either benzocamine or AMP-PNP. Since benzocamine binds to the central complex (Fig. 3a) one has to conclude that this intermediate presumably includes a phosphorylated enzyme species of the transport ATPase protein. Dieterle [21] has suggested that in acetyl phosphate containing assays a ternary phosphoprotein complex is formed after addition of ADP and AMP-PNP. Similarly, Nakamura et al. [22] inferred from kinetic data of pNPP-splitting the presence of a \( p \)-nitrophenol binding

\[ V_{\text{p}} = [\text{MgATP}] \]

\[ V_{\text{p}} = [\text{ADP}] \]

\[ V_{\text{p}} = [\text{AMP-PNP}] \]

Fig. 3. Combined Dixon Hanes-Woolf-plots (\( V_{\text{p}} \times [\text{MgATP}] \) versus inhibitor concentration. a) Replotting of Fig. 1c. b) Replotting of Fig. 2d.

Fig. 4. Effect of benzocamine and AMP-PNP on the phosphoprotein formation in assays containing ADP. Ordinate: Phosphoprotein formation. Abscissa: Concentration of inhibitor. 20 mM Histidine-buffer (pH 7.0), 0.5 mg prot/ml assay, \( \mu = 0.1 \), 0 °C. a) With benzocamine. 1 mM MgATP, 1 mM ADP, 0.5 mM Mg\(^{2+}\), 0.4 \( \mu \)M Ca\(^{2+}\). b) With AMP-PNP. 3 mM MgATP, 1 mM ADP, 0.1 mM Mg\(^{2+}\), 8 \( \mu \)M Ca\(^{2+}\).
free phosphorylated intermediates do not combine with DIO 9. From the primary Dixon plots, however, it is impossible to localize the enzyme target of DIO 9 inhibition. In order to obtain detailed information the Dixon procedure was extended.

A number of experiments was carried out varying the concentrations of DIO 9 and of a certain ligand. The intercept on the abscissa \( (p) \) of the primary plots according to Dixon were determined and subsequently replotted against the corresponding ligand concentration. The \( p \) value depends on ligand concentrations \([L] \) and on the equilibrium constants between ligands and inhibitors of the corresponding enzyme species but is independent of the inhibitor concentration (see Eq. (6)). From the behaviour of the \( p \) value when the concentration of a certain ligand is varied one can specify the blocked intermediate. Figure 5 shows all possible patterns of plotting \( p \) versus \([L] \) and comments on the corresponding inhibition mechanism.

The analysis of DIO 9 inhibition on the ADP-ATP-exchange activity is presented in Fig. 6. The \( p \) value shows a non-linear increase versus \( \text{Mg}^{2+} \) concentration, a linear increase versus the square of \( \text{Ca}^{2+} \) concentration (as mentioned in the introduction, the controlled variable should be the square of \([\text{Ca}^{2+}] \) since the sarcoplasmic reticulum transport enzyme is activated by two \( \text{Ca}^{2+} \) ions) and a nonlinear decrease versus ADP concentration. According to the possibility described in Fig. 5 one must conclude that DIO 9 interacts with the enzyme species E and MgE (Eq. (1)).
Hence the $p$ value is given by:

$$
P = \frac{K_A K_I K_I}{(K_A K_I + K_I[Mg])} + \frac{[Mg]K_K K_I}{(K_A K_B K_I + K_B K_I[Mg])} + \frac{[Mg][Ca^2+]K_I K_I}{(K_A K_B K_C K_I + K_B K_C K_I[Mg])} + \frac{K_D[Mg][Ca^2+]K_I K_I}{[ADP](K_A K_B K_C K_I + K_B K_C K_I[Mg])}. \quad (6)
$$

Eq. (6) fulfills the feature of the curves appearing in Fig. 6a–c. None of the equations of the $p$ value derived from another version of inhibition mechanism can meet the observed pattern (Fig. 6a–c). The results of Fig. 6 conversely establish another essential point in the reaction sequence (Eq. (1)), namely that Mg$^{2+}$ ions bind to the enzyme before the enzyme is activated by Ca$^{2+}$-binding. The inverse binding sequence of Mg$^{2+}$- and Ca$^{2+}$-ions does not result in the pattern of Fig. 6a and b.

It is well known that the ATP-splitting of the sarcoplasmic reticulum enzyme is inhibited if the Ca$^{2+}$ concentration is raised above the optimum concentration [23–26]. The rate of ATP-ADP-exchange is also inhibited at relatively high Ca$^{2+}$ concentrations [27] and the inhibition range depends on the Mg$^{2+}$ concentration in the assay (Fig. 7).

Fig. 8a, b shows the results of the analysis of the inhibitory effect of Ca$^{2+}$ on the ATP-ADP-exchange rate. The $p$ value exhibits linear increase versus Mg$^{2+}$ concentration and non-linear decrease versus ADP concentration. According to the predictions illustrated in Fig. 5 Ca$^{2+}$ at high concentrations binds exclusively to the ligand free enzyme species ($E$ in Eq. (1)) apparently in competition with Mg$^{2+}$ ions.

In contrast to the conventional Dixon plots the new plotting method furnishes all necessary information that is needed to localize the target intermediate. Furthermore the criterion of this method is the shape of the graph which is in general much easier to judge objectively than parallelity of two or more straight lines.

From the experimental data used for Fig. 8a, the Hill coefficient of Ca$^{2+}$ binding to the Mg$^{2+}$ activation site was calculated and amounts to 0.97 ± 0.07. It means that one Ca$^{2+}$ ion is needed to expel Mg$^{2+}$ from its binding site.

From kinetic investigations of the transport ATPase activity Vianna [7] described Mg$^{2+}$ to be a Ca$^{2+}$ competitor and pointed out the mutual dependence of the optimum concentrations of Ca$^{2+}$ and Mg$^{2+}$ within the activating concentration range of ATP-splitting. The competition between Ca$^{2+}$ and Mg$^{2+}$ ions described here (Fig. 8) does not take place at the high affinity Ca$^{2+}$ binding site of the
enzyme discussed by Vianna but at the Mg\(^{2+}\) binding site. Thus, the replacement of Mg\(^{2+}\) ions by Ca\(^{2+}\) ions causes an inhibition of the phosphorylation of the enzyme.

Dupont [28] has suggested a conversion of a magnesium-phosphoenzyme \([2\text{Ca} \cdot E \cdot Mg \cdot P]\) to a calcium-phosphoenzyme \([2\text{Ca} \cdot E \cdot Ca \cdot P]\) which is also ADP sensitive. The result of the Fig. 8 does not absolutely exclude this possibility. However, it indicates clearly that the exchange between Ca\(^{2+}\) and Mg\(^{2+}\) ions at the Mg\(^{2+}\) binding site mainly takes place via the ligand free intermediate while the Ca\(^{2+}\)-Mg\(^{2+}\)-exchange on the other intermediate can be neglected.