The influence of free radicals and other reactive oxygen species on pharmacological actions in the cardiovascular system

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Chapter 3

Possible mechanism of the negative inotropic effect of $\alpha_1$-adrenoceptor agonists in isolated rat left atria after exposure to reactive oxygen species
NEGATIVE INOTROPIC EFFECT OF \( \alpha_1 \)-ADRENOCEPTOR AGONISTS

Introduction

Under most experimental conditions, the stimulation of myocardial \( \alpha_1 \)-adrenoceptors causes a positive inotropic response (for review see Li et al., 1997), but there also exist several reports on negative inotropic actions of \( \alpha_1 \)-adrenoceptor agonists. For example, negative inotropic effects have been described at high electrical stimulation frequencies in rabbit papillary muscle (Endoh and Schumann, 1975), upon simultaneous activation of \( \alpha \)- and \( \beta \)-adrenoceptors (Danziger et al., 1990) and upon simultaneous activation of \( \alpha_1 \)-adrenoceptors and endothelin receptors (Yang et al., 1996).

We have previously reported that reactive oxygen species (ROS), generated by electrolysis of the organ bath solution, reduce the inotropic responses to various inotropic stimuli in isolated rat left atria. These inotropic stimuli include lowering of stimulation frequency, sodium withdrawal, extracellular Ca\(^{2+}\) addition, the adenyl cyclase activator forskolin, the cyclic AMP analogue dibutyryl-cAMP, and agonists at \( \beta \)-adrenoceptors (Peters et al., 1997). Thus, electrolysis and concomitant ROS generation appear to impair cardiac contractility in general. However, the alterations of the responses to the \( \alpha_1 \)-adrenoceptor agonists, methoxamine, cirazoline and ST 587 were affected in a different manner, since these agonists surprisingly caused negative inotropic actions in electrolysis-treated atria (Peters et al., 1997). Since negative inotropic effects in electrolysis-treated atria were not observed with any other inotropic manoeuvre, the present study was designed to investigate the underlying mechanism(s) in more detail.

The signal transduction mechanism of the \( \alpha_1 \)-adrenoceptor is complex and not understood in detail. Stimulation of the \( \alpha_1 \)-adrenoceptor leads to a rapid breakdown of phosphoinositide by phospholipase C, which results in the formation of inositol 1,4,5 trisphosphate (IP\(_3\)) and 1,2 diacylglycerol. IP\(_3\) mobilizes Ca\(^{2+}\) from intracellular stores in various tissues including myocardial sarcoplasmic reticulum (Fabriato, 1986; Nosek et al., 1986), although there is also one contradictory report (Movsesian et al., 1985). Diacylglycerol is the endogenous activator of protein kinase C (PKC) which can target several substrates in the myocardial cell such as phospholamban (Movsesian et al., 1984), C-protein (Venema and Kuo, 1993), troponin I and T (Kato et al., 1983), the Na\(^+\)/H\(^+\) exchanger (Moolenaar et al., 1984), and possibly the Na\(^+\)/K\(^+\) ATPase (Feschenko and Sweadner, 1994). \( \alpha_1 \)-Adrenoceptor stimulation enhances the Na\(^+\)/H\(^+\) exchange via a PKC-mediated mechanism, resulting in an intracellular alkalinisation and the accumulation of Na\(^+\). A subsequent activation of the Na\(^+\)/Ca\(^{2+}\) exchange might result in an enhanced Ca\(^{2+}\) influx and hence a rise in contractile force (Iwakura et al., 1990). It has been reported that intracellular alkalinisation induces sensitisation
of myofilaments (Fabiato and Fabiato, 1978) and this mechanism could be responsible for the sustained positive inotropic effect. However, because these hypotheses are based mainly on experiments with rather unspecific amiloride derivatives, the results may only be interpreted with great caution (Pucéat, 1995). Phosphorylation of tropinin I and T by PKC decreases the rate of crossbridge cycling and reduces the myofibrillar actomyosin Mg ATPase activity, and will thus decrease the force of contraction (Venema and Kuo, 1993; Strang and Moss, 1995). Several studies have shown that the Na+/K+ ATPase is involved in the α1-adrenoceptor signal transduction cascade. Shah et al., (1988) have shown that the activation of the sodium pump after α1-adrenoceptor stimulation is sensitive to pertussis toxin. However, other groups have provided evidence that, at least in vitro, the Na+/K+ ATPase is a good substrate for PKC. Whether phosphorylation of the sodium pump leads to an increase or decrease of the enzyme activity is still unclear (Carranza et al., 1996; Logvinenko et al., 1996). Among the listed components of α1-adrenergic signal transduction in the heart, phosphorylation of the troponins and activation of the Na+/K+ ATPase will reduce inotropy while the other processes will enhance it (for overview see figure 6).

Based on these findings we have hypothesized that oxidative stress leads to biochemical changes which resulted in a an altered ratio of the negative and positive inotropic components of the α1-adrenoceptor signal transduction pathway. To test this hypothesis we have performed direct measurements of methoxamine-induced phospholipase C and Na+/K+ ATPase activity changes, and also used ouabain to block the Na+/K+ ATPase, and calphostin C to inhibit the PKC-mediated responses.

Methods

Electrolysis treatment and contraction studies
Male Wistar rats (Iffa Credo, Les Oncins, France) weighing 240-300 g were sacrificed by stunning and decapitation. Electrolysis treatment and contraction measurements were performed as previously described in detail (Peters et al., 1997). Briefly, the hearts were removed quickly and placed in a Tyrode's solution of the following composition (in mM): NaCl 119; KCl 4.5; MgCl2 0.5; CaCl2 2.5; glucose 11; Tris 30 at pH 7.5 at room temperature, and were bubbled with 100% oxygen. The isolated left atria were suspended in water jacketed organ baths (kept at 37°C and gassed with 100% oxygen) filled with 5 ml Tyrode's solution (pH adjusted to 7.5 at 37°C), and connected with a silk thread to an isometric force transducer. The atria were paced with a field stimulator (Hugo Sachs Electronic, Germany) at a frequency of 3 Hz (0.5 V, 5 ms). The isometric force of contraction was recorded on a
Maclab/8e data acquisition system (ADInstruments, Australia). The resting tension was adjusted to 5 mN and the atria were allowed to equilibrate for at least 45 min. At 20 min. intervals the medium was replaced with fresh buffer. After the equilibration period, ROS were generated by electrolysis of the medium using two additional circular platinum wire electrodes (each 0.75 cm in length) at the bottom of the organ baths (Ø 1.4 cm). A constant current of 30 mA, generated by a 6 channel constant current device (Dept. of Electronics, Academic Medical Centre, Amsterdam), was applied for 75 s. Agonists were added 30 min. after the electrolysis procedure, to ensure that the tissue was damaged significantly. Inhibitory drugs were added 15 min. prior the addition of agonist. Unless indicated otherwise the atria remained in the electrolysis-treated buffer throughout the experiment. The concentrations of agonists used in this study, gave a maximum response in control atria based on concentration response curves (Peters et al., 1997).

[^3H] Inositol phosphate assay
Basal and methoxamine-induced inositol phosphate formation were measured in atrial slices according to the method of Eid and De Champlain (1988). For this purpose the atria were removed from the organ bath 30 min. after electrolysis and cut into small slices of approximately 2-3 mg. Individual slices were labeled with 10 µCi/ml myo[^3H]inositol for 60 min. at 37°C in 3 ml vials containing 300 µl Tyrode's solution from the organ bath. Thereafter, 10 µl LiCl solution (final concentration 10 mM) was added to prevent degradation of inositol monophosphates by inositol monophosphatase. Twenty min. later 20 µl methoxamine solution (final concentration 300 µM) or saline was added to the vials, and the incubation continued for another 60 min. Thereafter, the slices were washed twice with 1 ml ice-cold buffer, and the reaction was stopped by the addition of 330 µl ice-cold methanol and 660 µl chloroform. The vials were vortexed for 30 s and centrifuged 15 min. at 750 g at 4°C. Aliquots of the upper phase (450 µl) were placed on columns containing 1 ml of AG 1-X8 resin (200-400 mesh, formate form). The columns were washed twice with 5 ml distilled water. Glycerophosphoinositides were eluted with 2 x 5 ml 60 mM ammonium formate solution.[^3H]IP's were eluted with 2 x 1 ml of 0.1 M formic acid/1 M ammonium formate. The latter fraction was added to 8 ml scintillation fluid, and radioactivity was measured in a liquid scintillation counter at 42% efficiency. In experiments with doxazosin (1 µM) and phentolamine (1 µM), the α-adrenoceptor antagonists were added to the medium in the organbath 10 min. after electrolysis. Experiments were performed in quadruplicate.

Na^+/K^+ ATPase activity measurement
Na^+/K^+ ATPase activities were measured by determination of the K^+-dependent p-nitrophenyl
phosphatase activity (Larsen and Kjeldsen, 1995) in crude atrial homogenates. Briefly, atria were removed from the organ bath 10 min. after addition of methoxamine (300 μM) or saline. The atria (10 mg wet weight tissue/ml) were washed and homogenized with an Ultraturrax (15 s full speed, 0°C) in buffer containing 30 mM histidine, 2 mM EDTA and 250 mM sucrose (pH 7.2).

For the assay, 100 μl of tissue homogenate was added to 800 μl reaction buffer (25 mM histidine at pH 7.4, 15 mM MgCl₂ and 50 mM KCl or 100 mM NaCl). After 10 min. preincubation at 37°C, the reaction was initiated by addition of 100 μl 100 mM p-nitrophenylphosphate to the reaction mixture, and incubated for 30 min. at 37°C. The reaction was stopped by the addition of 2 ml ice-cold buffer containing 500 mM Tris and 55 mM EDTA. The formation of p-nitrophenol was quantified spectrophotometrically at a wavelength of 410 nm with a Zeiss Specord UV/Vis S10 spectrophotometer. The K⁺ dependent p-nitrophenyl phosphatase activity was measured as the difference in activity in the presence or absence of K⁺. Enzyme activity was calculated using the molar absorption coefficient of p-nitrophenol (1.81*10⁵) and expressed as μmol/min/g wet weight tissue.

**Statistics**

Data are expressed as means ± SEM. Student’s t-test (two tailed, unpaired) and ANOVA (Dunnet) were used, and P values < 0.05 were considered to be statistically significant.

**Chemicals**

Endothelin-1, isoprenaline bitartrate, methoxamine HCl and phentolamine HCl were purchased from Sigma Chemical, St Louis, MO, USA. p-Nitrophenyl phosphate and calphostin C from ICN Biomedicals, Zoetermeer, the Netherlands, myo-[³²P]inositol from Amersham, Buckinghamshire, UK. Resin AG 1-x8 was purchased from BIORAD, Hercules CA, USA. Doxazosin mesylate and ouabain were obtained from OPG, Utrecht, The Netherlands. All drugs were dissolved in distilled water. Calphostin was dissolved in 99% DMSO.

**Results**

**Contraction experiments**

The initial force of contraction prior to application of electrolysis was 9.4 ± 0.3 mN (n=10). Whereas the force of contraction remained stable in control atria, a continuous deterioration was observed in atria subjected to electrolysis. Accordingly, the basal force of contraction determined 30 min. after electrolysis was only 3.6 ± 0.5 mN (i.e. approximately 40% of initial force of contraction) while it was 8.6 ± 0.4 mN (i.e. approximately 90% of initial force of contraction) in control preparations not subjected to electrolysis. Methoxamine (300
**Negative inotropic effect of α₁-adrenoceptor agonists**

**Figure 1**

Comparison of the inotropic effects of 300 μM methoxamine, 30 nM endothelin and 10 μM isoprenaline in control atria (closed bars) and in atria subjected to oxidative stress (open bars), measured 10 min. after their addition. *P < 0.05 compared to their controls (two-tailed Student's t-test; n = 4-8).

300 μM methoxamine increased contractile force by 1.6 ± 0.2 mN (n = 4) in control atria but decreased contractile force in electrolysis-treated atria by 2.0 ± 0.1 mN (n = 5, P < 0.05, Figure 1), as determined 10 min. after methoxamine addition. In contrast, the positive inotropic effects of endothelin-1 (30 nM) and isoprenaline (10 μM) were reduced from 2.6 ± 0.3 to 1.3 ± 0.1 mN and from 2.6 ± 0.3 to 1.7 ± 0.2 mN, respectively, by electrolysis treatment (n = 6, P < 0.05; Figure 1) but these agents did not cause any reduction of contractile force.

We have tested the antagonism of the α₁-adrenoceptor antagonist doxazosin under two conditions: in to electrolysis subjected medium and in refreshed medium. Doxazosin (10 μM) did not block the negative inotropic effect of methoxamine in electrolysis-treated atria when the buffer was not refreshed prior antagonist addition (Figure 2, panel A). However, doxazosin significantly inhibited the negative inotropic effect of methoxamine when the medium was refreshed prior antagonist addition (Figure 2, panel B). Doxazosin had no influence on the gradual decrease in contractile force.

**Figure 2**

The effect of changing the medium on the antagonism of the negative inotropic effect of 300 μM methoxamine (M) by 1 μM doxazosin (D) in electrolysis (E) treated atria. A) results in electrolysis-treated medium, B) in fresh medium after electrolysis. Data are expressed as % of initial values (9.4 ± 0.3 mN).
normally seen (i.e. without the addition of methoxamine) after electrolysis. Ouabain (10 μM, added 15 min. after electrolysis) had no significant influence on the contractile force of control and electrolysis-treated atria; neither did it change the inotropic response to 300 μM methoxamine in control atria. However, in the presence of ouabain, 300 μM methoxamine had no negative inotropic effect in electrolysis-treated atria. Accordingly, the force of contraction 10 min. after methoxamine addition (that is 40 min. after electrolysis) was 0.8 ± 0.2 mN in absence, and 4.3 ± 0.5 mN in the presence of ouabain (and 2.5 ± 0.3 mN for electrolysis without ouabain; n = 5 each, P < 0.05; Figure 3).

The protein kinase C inhibitor calphostin C (50 nM, added 15 min. after electrolysis) did not significantly influence contractile force in control and electrolysis-treated atria, and neither did it alter the methoxamine (300 μM) induced positive inotropic effect in control atria. Calphostin C completely blocked the negative inotropic effect of methoxamine in electrolysis treated atria and partially restored the positive inotropic effect (figure 3). Accordingly, the force of contraction 10 min. after methoxamine addition amounted to 0.8 ± 0.2 mN in the absence and to 4.4 ± 0.4 mN in the presence of calphostin C (and 2.5 ± 0.3 mN for electrolysis only; n = 5 each, P < 0.05; figure 3).

[3H]inositol phosphate assay
Basal inositol phosphate formation was not significantly different between the control (352 ± 46 cpm) and the electrolysis-treated organs (258 ±
**Figure 4**

Inositol phosphate ([3H]IP) formation induced by α₁-adrenoceptor stimulation with 300 µM methoxamine in slices of control atria and of atria subjected to oxidative stress without medium refreshment. Phentolamine (1 µM) and doxazosin (1 µM) were added to the organ bath 10 min. after electrolysis. Slices were prepared and incubated with myo-[3H]inositol 30 min. after electrolysis. Note the incomplete inhibition by the antagonists in the electrolysis group. Data are expressed as % over basal (control 352 ± 46 cpm, electrolysis 258 ± 17 cpm). *P < 0.05 compared to methoxamine control (n = 4-5).

A quantitatively similar enhancement was also seen in electrolysis-treated atria (126 ± 25% over basal, n = 5).

**Na⁺/K⁺ ATPase activity**

The Na⁺/K⁺ ATPase activity was measured in crude homogenates of control or electrolysis-treated atria by determination of the K⁺-dependent p-nitrophenyl phosphatase activity. Basal activity was significantly lower in electrolysis-treated compared to control atria (1.01 ± 0.12 vs. 1.72 ± 0.16 µmol/min/g, n = 5, P < 0.05). When calphostin C (50 nM) or vehicle (DMSO <0.01%) was added to the organ bath 15 min. after electrolysis, the electrolysis did not significantly decrease basal Na⁺/K⁺ ATPase activity (1.43 ± 0.05 µmol/min/g and 1.28 ± 0.09 for vehicle only, n = 5). Addition of ouabain (10 µM) directly to the reaction mixture reduced the basal activities by approximately 56%, thus confirming the ability of our assay to detect alterations in sodium-pump activity (Larsen and Kjeldsen, 1995).

Methoxamine treatment of the atria decreased the Na⁺/K⁺ ATPase activity in control atria by 136 ± 19% over basal (n = 3), while the corresponding increase in electrolysis-treated atria was only 68 ± 15% over basal (n = 5, P < 0.05 vs. control in an unpaired t-test). Doxazosin (1 µM) and phentolamine (1 µM) almost completely inhibited methoxamine stimulated inositol phosphate formation in control organs (Figure 4), but the inhibition was considerably weaker and no longer statistically significant in electrolysis treated atria (Figure 4). When these experiments were repeated with fresh buffer for labeling, somewhat different results were obtained: The enhancements of inositol phosphate formation by methoxamine in control atria (146 ± 36% over basal, n = 5) were similar to those seen in control atria without buffer refreshment.
Addition of vehicle (DMSO, <0.01%) alone to the organ bath had no influence on the methoxamine-induced increase in Na\textsuperscript{+}/K\textsuperscript{+} ATPase activity in electrolysis-treated atria.

**Discussion**

We have previously shown that electrolysis treatment attenuates the inotropic responses to reduced stimulation frequency, to the elevation of extracellular Ca\textsuperscript{2+}, to withdrawal of extracellular Na\textsuperscript{+}, the \(\beta\)-adrenoceptor agonist, isoprenaline, and to forskolin and db-cAMP. On the other hand, electrolysis treatment appears to reverse the positive inotropic effects of the \(\alpha_1\)-adrenoceptor agonists, methoxamine, cirazoline and ST 587 into opposite, negative inotropic actions (Peters et al., 1997). Accordingly, electrolysis appears to involve a general impairment of inotropic responses to almost all stimuli and, unexpectedly, a reversal into negative responses which is limited to \(\alpha_1\)-adrenoceptor agonists. The present study was designed to investigate the mechanisms underlying the latter surprising phenomenon, that is the reversal into negative inotropic responses for the \(\alpha_1\)-adrenoceptor agonists in electrolysis-treated, isolated left atria of the rat.

Electrolysis of the bath fluid generates hydroxyl radicals, superoxide anions, hydrogen peroxide, hypochlorite and singlet oxygen in a current- and time-dependent manner (Jackson et al., 1986; Chahine et al., 1991; Niu et al., 1995; de Keulenaer et al., 1995). While most of these ROS are believed to be short-lived, some of them (or lipid peroxidation products like malondialdehyde and hydroxynonenal) may survive sufficiently long to oxidize some of the pharmacological agents being used. Therefore, we have performed our functional and inositol phosphate experiments both in electrolysis-treated and refreshed bath fluids. This procedure allows us to distinguish between biological ROS actions on the atria and physico-chemical effects on the molecules of the agonists and antagonists. Our data suggest that both types of effects may indeed occur: Firstly, the antagonists doxazosin and phentolamine failed to inhibit the methoxamine effects in electrolysis-treated atria in

Figure 5

Na\textsuperscript{+}/K\textsuperscript{+} ATPase activity, measured as K\textsuperscript{+}-dependent \(p\)-nitrophenyl phosphatase activity, after \(\alpha_1\)-adrenoceptor stimulation with 300 \(\mu\)M methoxamine in crude homogenates of control atria and of atria exposed to electrolysis. Calphostin C (50 nM) and methoxamine were administered to the medium in the organ bath 15 min. and 30 min. after electrolysis, respectively. Homogenates were prepared 10 min. after addition of methoxamine or saline. Data are expressed as % over basal (control: 1.72 ± 0.16, electrolysis: 1.01 ± 0.12 and calphostin C: 1.43 ± 0.05 \(\mu\)mol \(p\)-nitrophenol/min/g). * \(P < 0.05\) compared to control, \(n=5-7\).
both, the present and our previous study (Peters et al., 1997) when added directly to the electrolysis-treated medium. However, they inhibited the methoxamine effects under control conditions and after addition to electrolysis-treated atria in the presence of fresh buffer. Consequently, electrolysis-generated ROS, or lipid peroxidation products, appear to chemically damage, or interfere with the action of the antagonists. Secondly, the negative inotropic effect of methoxamine was observed when the agonist was added to both, electrolysis-treated and fresh medium. For this reason, the negative inotropic effects appear to result from changes within the atria rather than from chemical alterations of methoxamine (present study) or the \( \alpha_1 \)-adrenoceptor agonists cirazoline and ST 587 (Peters et al., 1997).

\( \alpha_1 \)-Adrenoceptor agonists clearly differ from the other inotropic stimuli investigated in our previous study (Peters et al., 1997) since they couple to phospholipase C with the subsequent elevation of intracellular Ca\(^{2+} \) and activation of PKC. This raised the possibility that the negative inotropic effects of the \( \alpha_1 \)-adrenoceptor agonists following electrolysis may be related to alterations of the PLC signalling pathway. On the other hand, the inotropic responses to another PLC-coupled receptor-agonist, endothelin-1 (Vigne et al., 1989; Vogelsang et al., 1994) proved impaired but not reversed. The experiments with electrolysis-treated and fresh medium have shed additional light on a possible alteration of PLC as the cause for the negative inotropic effects of \( \alpha_1 \)-adrenoceptor agonists. Accordingly, we observed that the stimulation of PLC by methoxamine was indeed attenuated by electrolysis when the medium from the organ bath was used. However, the PLC responses were restored by the use of fresh medium. This is in contrast to the functional data which showed negative inotropic responses to methoxamine with electrolysis-treated and refreshed bath fluid. It may therefore be possible that ROS impair PLC responses and hence contribute to the attenuated inotropic responses, for instance those for endothelin-1. On the other hand, this phenomenon does not explain why the positive inotropic responses to \( \alpha_1 \)-adrenoceptor agonists (which occur with fresh and old buffer) were reversed into negative ones. Possible alternative candidates include signal transduction steps which occur distally or in parallel to PLC, for instance PKC or Na\(^+\)/K\(^+\) ATPase.

Cardiac \( \alpha_1 \)-adrenoceptor stimulation activates PKC and, under some circumstances, may stimulate Na\(^+\)/K\(^+\) ATPase (Endoh, 1991). This latter effect may be partially mediated by PKC, but there is still some debate as to whether phosphorylation of the Na\(^+\)/K\(^+\) ATPase will increase or decrease the activity of this enzyme (Carranza et al., 1996; Logvinenko et al., 1996). In the present study the PKC inhibitor, calphostin C, and the Na\(^+\)/K\(^+\) ATPase inhibitor, ouabain, both prevented the
negative inotropic effects of methoxamine by electrolysis treatment. These results indicate the involvement of the \( \text{Na}^+/\text{K}^+ \) ATPase and possibly PKC in the negative inotropic effects of methoxamine after oxidative stress. Our previous observation that the PKC inhibitor chelerythrine (2 \( \mu \text{M} \)) did not prevent the negative inotropic activity of methoxamine (Peters et al., 1997), may be related to the fact that calphostin C and chelerythrine are structurally distinct inhibitors of PKC which may interfere with its inhibiting activity by different mechanisms (Gordge and Ryves, 1994).

For this reason, we have investigated the regulation of cardiac \( \text{Na}^+/\text{K}^+ \) ATPase activity by electrolysis and \( \alpha_1 \)-adrenoceptor stimulation in a direct manner. Our assay only measures changes in activity due to modifications of the enzyme itself (phosphorylation and/or conformational changes due to ROS exposure) but not those due to differences in the electrochemical \( \text{Na}^+ \) or \( \text{K}^+ \) gradients, because the activities were measured in tissue homogenates. Our data confirm previous observations that \( \text{Na}^+/\text{K}^+ \) ATPase activity is reduced by oxidative stress (Huang et al., 1994). The latter effect was
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blocked by the PKC inhibitor, calphostin C, but also by its vehicle, DMSO (<0.01%). As DMSO is known to have hydroxyl radical scavenger activity, these data suggest that the observed effect of calphostin C on basal Na$^+$/K$^+$ ATPase activity may be related to ROS scavenging by its vehicle rather than to PKC inhibition. The inhibition of Na$^+$/K$^+$-ATPase by methoxamine by approximately 15% in control atria was reversed into an approximately 50% stimulation in electrolysis-treated atria. Interestingly, this stimulation of Na$^+$/K$^+$ ATPase activity by methoxamine in electrolysis-treated atria was prevented by the PKC inhibitor calphostin C but not by its vehicle DMSO, indeed suggesting that this effect was mediated via PKC. The finding that calphostin C completely inhibited the methoxamine-induced increase of Na$^+$/K$^+$ ATPase activity in electrolysis-treated atria also indicates that under our experimental conditions phosphorylation by PKC may increase Na$^+$/K$^+$ ATPase activity.

On the basis of these data we propose the following model to explain the negative inotropic effects of $\alpha_1$-adrenoceptor agonists by electrolysis (Figure 6). Cardiac $\alpha_1$-adrenoceptors can couple to a multitude of signalling pathways which may either enhance or reduce cardiac contractility (Endoh, 1991). Electrolysis treatment may affect these signalling pathways in multiple ways to alter the balance between positive and negative inotropic events. Consequently, chemical destruction of the agonists, impairments of PLC and adenylyl cyclase (Peters et al., 1997) activities and of the general contractile machinery of the cardiomyocyte may occur. These alterations may explain the reduced inotropic effects of all tested stimuli in electrolysis-treated atria. However, they do not explain the reversal into negative inotropic effects which appear to be specific for $\alpha_1$-adrenoceptor agonists. Hence we propose that electrolysis alters the coupling between $\alpha_1$-adrenoceptors, PKC and Na$^+$/K$^+$ ATPase to yield activation instead of inhibition of Na$^+$/K$^+$ ATPase. It has been shown that phosphorylation of the Na$^+$/K$^+$ ATPase by PKC is conformation-dependent (Feschenko and Sweadner, 1994). A possible explanation for the increased PKC-mediated Na$^+$/K$^+$ ATPase activity after methoxamine stimulation in atria subjected to electrolysis could be that ROS induce a conformational change of the Na$^+$/K$^+$ ATPase, and thereby make the enzyme more susceptible to phosphorylation by PKC.
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