Effect of Norepinephrine and Cyclic AMP on Intracellular Sodium Ion Activity and Contractile Force in Canine Cardiac Purkinje Fibers

Mark S. Pecker, Wook-Bin Im, Jong K. Sonn, and Chin O. Lee

In cardiac muscle cells catecholamines increase Na efflux and K influx, and, under certain conditions, hyperpolarize the cell membrane. Studies on cardiac muscle utilizing Na+-selective micro-electrodes have shown that catecholamines decrease intracellular Na ion activity (a^N) (1-3). This decrease is blocked by cardiotonic steroids (4) or propranolol (5). These findings suggest that catecholamines stimulate the Na^+-K^+ pump. Another possibility for the decrease in a^N caused by catecholamines, that they decrease passive Na influx, has not been extensively examined.

The present experiments explore the decrease in a^N induced by norepinephrine in canine cardiac Purkinje fibers, and the extent to which analogues of cAMP mimic this effect. In order to determine if the fall in a^N was due to intercellular K^+ accumulation, we examined the effects of norepinephrine on a^N in the presence of high K^+ solution. We also examined the effect of tetrodotoxin on the effect of norepinephrine. This served two purposes. First, since exposure to high K^+ solution was due to intercellular K^+ accumulation, we examined the effects of norepinephrine on a^N in the presence of high K^+ solution. Second, we wanted to see if the effect of norepinephrine depended on the activity of the fast sodium channel.

Some of these results have been previously published in abstract form.
Materials and Methods

Mongrel dogs of either sex weighing 8–12 kg were anesthetized by intravenous administration of sodium pentobarbital (30 mg/kg). The heart was quickly excised through an intercostal incision and transferred to oxygenated Tyrode solution at room temperature. Free running bundles of Purkinje fibers of 0.5–1.0 mm diameter and 5–12 mm length were dissected from both ventricles. A fiber bundle was mounted in a narrow channel of a muscle chamber, with one end fixed to the Sylgard floor of the chamber and the other end connected to a tension transducer (Model 405, Cambridge Technology, Cambridge, Mass.) by means of a silver wire 25 μ in diameter.15 Oxygenated Tyrode solution was perfused through the channel at a constant rate so that solution changes around the tissue took place in several seconds. Normal Tyrode solution contained (in mM) 137 NaCl, 5.4 KCl, 1.8 CaCl₂, 1.05 MgCl₂, 11.9 NaHCO₃, 0.45 NaH₂PO₄, and 5.0 dextrose. High K (16.2 mM) Tyrode solution was made by replacing 10.8 mM NaCl with KCl in the normal Tyrode solution. K-free Tyrode solution was made by omitting the KCl without other changes in the normal Tyrode solution. The bath temperature was 36–37°C. Solutions were gassed with a mixture of 97% O₂ and 3% CO₂, and the pH of all solutions were 7.3–7.4. The Purkinje fibers stimulated at a constant rate of 1.0 Hz throughout the experiments by stimulating electrodes connected to a stimulator (Model 301 T; W-P Instruments, New Haven, Conn.) through a stimulus isolation unit (Model 305-1, W-P Instruments, New Haven, Conn.) The sensitivity of the force transducer was 50 mV/mg.

One milligram of Tetrodotoxin (Sankyo Co., Ltd., obtained through Calbiochem-Behring Corp., LaJolla, Calif.) was dissolved in 2 ml of deionized water, and this stock solution was kept refrigerated. A stock solution of norepinephrine (Levophed Bitartrate, Breon Calif.) was dissolved in 2 ml of deionized water, and a stock solution of digitoxin (Lanoxin, Sankyo Co., Ltd.) was dissolved in 40 ml of 2% dimethyl sulfoxide (Sigma Chemical Co., St. Louis, Mo.) in deionized water was prepared and, prior to use, diluted with the appropriate solution. N°, 2'-0-dibutryl-adenosine 3':5'-cyclic monophosphate (DBcAMP) and 8-(4-chlorophenylthio)-adenosine 3', 5'-cyclic monophosphate (8-ClPheScAMP) (Sigma Chemical Co., St. Louis, Mo.) were dissolved in Tyrode solution immediately prior to use.

Intracellular Na ion activity (aNa) was measured with Na⁺-selective microelectrodes made with the neutral carrier ETH 227.16 Construction and calibration of the Na⁺-selective microelectrodes have been described in detail.17,18 The Na⁺-selective electrodes were calibrated before and after each experiment. The Purkinje fibers were impaled with both conventional and Na⁺-selective microelectrodes. The distance between the impalements was less than 1 mm. aNa of canine cardiac Purkinje fibers stimulated at a constant rate of 1.0 Hz was determined as described previously.15,19 In order to measure aNa continuously in electrically driven fibers we used two identical low-pass filters (with a fixed frequency of 0.24 Hz) to remove the fluctuations in transmembrane potential recorded by conventional and Na⁺-selective microelectrodes. In the text, Vm refers to the filtered transmembrane potential.15

All results are expressed as mean ± standard deviation. Changes of aNa within each intervention were analyzed by paired t test. Correlations were determined by linear regression. Comparisons between different experiments were analyzed by analysis of variance with pairwise t tests using the Bonferroni adjustment for multiple comparisons. All analyses were performed using the BMDP statistical software package.

Results

Effects of Norepinephrine in the Presence of Different K Concentrations

Figure 1 shows the effect of 10⁻⁴ M norepinephrine on filtered membrane potential (Vm). aNa, twitch tension (T) and action potential in a canine cardiac Purkinje fiber bathed in normal Tyrode solution. This experiment shows results that are similar to those reported previously. It demonstrates the effects of norepinephrine in this preparation. On exposure to 10⁻⁴ M norepinephrine twitch tension rapidly increases to a peak level and then decreases (Figure 1C) whereas aNa,
decreases (Figure 1B). Continuous exposure to norepinephrine maintains twitch tension at a level lower than the peak but higher than the control tension. Reexposure to normal Tyrode solution produces a rapid decrease in twitch tension. During recovery from norepinephrine the action potential duration shortened and the plateau and the maximum decrease of a\textsubscript{\text{ajv}} averaged 1.3 ± 0.4 mM to an average of 6.5 ± 0.5 mM in high K Tyrode solution (p < 0.01). 10\textsuperscript{-6} M norepinephrine in the presence of 16.2 mM [K\textsuperscript{+}] further decreased a\textsubscript{\text{ajv}} by 0.7 ± 0.4 mM to a level of 5.9 ± 0.2 mM (p < 0.02).

In order to ascertain that the fall in a\textsubscript{\text{ajv}} during exposure to high K Tyrode solution was due to pump stimulation, we tested the effect of norepinephrine in the presence of high [K\textsuperscript{+}] and strophanthidin. Figure 3 shows the effect of 10\textsuperscript{-6} M norepinephrine on a\textsubscript{\text{ajv}} in a fiber that was first bathed in 16.2 mM [K\textsuperscript{+}] and then in 16.2 mM [K\textsuperscript{+}] and 2.5 \times 10\textsuperscript{-6} M strophanthidin. This concentration of strophanthidin increased a\textsubscript{\text{ajv}} and also prevented norepinephrine from lowering a\textsubscript{\text{ajv}} just as it does in the setting of normal Tyrode solution. Similar results were obtained in 4 experiments in 4 tissues.

As a further evaluation of the possible effects of K\textsuperscript{+} conductance on the fall in a\textsubscript{\text{ajv}} we examined the effects of norepinephrine in the presence of K-free bathing solution. Figure 4 shows that K-free solution increased both tension and a\textsubscript{\text{ajv}}. As expected the fiber depolarized and became quiescent. Addition of norepinephrine did not produce a detectable decrease in a\textsubscript{\text{ajv}} although the membrane potential did hyperpolarize. Similar results were obtained in 6 experiments in 4 different tissues.

**Effects of Norepinephrine on a\textsubscript{\text{ajv}} in the Presence of Tetrodotoxin**

Figure 5 shows the effect of norepinephrine when a\textsubscript{\text{ajv}} was lowered by blocking the fast sodium channel with tetrodotoxin (TTX). Addition of 5 \times 10\textsuperscript{-6} M TTX decreased a\textsubscript{\text{ajv}} and twitch tension as shown in traces B and C respectively. The filtered membrane potential decreases (Figure 1B).

extracellular potassium causes over 90% of the maximum pump stimulation that can be attained by elevating external potassium.\textsuperscript{20,21} Under this condition, intercellular K\textsuperscript{+} accumulation due to an increase in K\textsuperscript{+} conductance should not further stimulate the Na\textsuperscript{+}–K\textsuperscript{+} pump. Changing the bathing solution from normal Tyrode to high K Tyrode solution decreased a\textsubscript{\text{ajv}}. Addition of 10\textsuperscript{-6} M norepinephrine caused a further decrease in a\textsubscript{\text{ajv}} as shown in Figure 2B. Washout of norepinephrine produced recovery of a\textsubscript{\text{ajv}} to the preexposure level. In 5 tests in 4 tissues, a\textsubscript{\text{ajv}} fell from an average of 8.8 ± 0.9 mM in normal Tyrode solution to an average of 6.5 ± 0.5 mM in high K Tyrode solution (p < 0.01). 10\textsuperscript{-6} M norepinephrine in the presence of 16.2 mM [K\textsuperscript{+}] further decreased a\textsubscript{\text{ajv}} by 0.7 ± 0.4 mM to a level of 5.9 ± 0.2 mM (p < 0.02).

In order to ascertain that the fall in a\textsubscript{\text{ajv}} during exposure to high K Tyrode solution was due to pump stimulation, we tested the effect of norepinephrine in the presence of high [K\textsuperscript{+}] and strophanthidin. Figure 3 shows the effect of 10\textsuperscript{-6} M norepinephrine on a\textsubscript{\text{ajv}} in a fiber that was first bathed in 16.2 mM [K\textsuperscript{+}] and then in 16.2 mM [K\textsuperscript{+}] and 2.5 \times 10\textsuperscript{-6} M strophanthidin. This concentration of strophanthidin increased a\textsubscript{\text{ajv}} and also prevented norepinephrine from lowering a\textsubscript{\text{ajv}} just as it does in the setting of normal Tyrode solution. Similar results were obtained in 4 experiments in 4 tissues.

As a further evaluation of the possible effects of K\textsuperscript{+} conductance on the fall in a\textsubscript{\text{ajv}} we examined the effects of norepinephrine in the presence of K-free bathing solution. Figure 4 shows that K-free solution increased both tension and a\textsubscript{\text{ajv}}. As expected the fiber depolarized and became quiescent. Addition of norepinephrine did not produce a detectable decrease in a\textsubscript{\text{ajv}} although the membrane potential did hyperpolarize. Similar results were obtained in 6 experiments in 4 different tissues.

**Effects of Norepinephrine on a\textsubscript{\text{ajv}} in the Presence of Tetrodotoxin**

Figure 5 shows the effect of norepinephrine when a\textsubscript{\text{ajv}} was lowered by blocking the fast sodium channel with tetrodotoxin (TTX). Addition of 5 \times 10\textsuperscript{-6} M TTX decreased a\textsubscript{\text{ajv}} and twitch tension as shown in traces B and C respectively. The filtered membrane potential decreases (Figure 1B). Continuous exposure to norepinephrine maintains twitch tension at a level lower than the peak but higher than the control tension. Reexposure to normal Tyrode solution produces a rapid decrease in twitch tension. During recovery from norepinephrine twitch tension falls to a value below that of control tension as seen in Figure 1C and 1D (undershoot). Note that during this undershoot of twitch tension a\textsubscript{\text{ajv}} is lower than the control a\textsubscript{\text{ajv}} in Tyrode solution (Figure 1B). The undershoot of twitch tension is consistent with the hypothesis that the low a\textsubscript{\text{ajv}} decreases intracellular calcium via Na\textsuperscript{+}–Ca\textsuperscript{2+} exchange. Twitch tension and a\textsubscript{\text{ajv}} then recover to preexposure values in concert with each other. During exposure to norepinephrine the action potential duration shortened and the early phase of the plateau was less negative. Diastolic membrane potential hyperpolarized slightly (Figure 1D). During washout of norepinephrine, the action potential duration recovered and the plateau and diastolic potential slightly depolarized. The changes in V\textsubscript{\text{m}} might reflect the changes in action potential shape. In 5 tests with 4 tissues, control a\textsubscript{\text{ajv}} was 8.0 ± 0.4 mM and the maximum decrease of a\textsubscript{\text{ajv}} averaged 1.3 ± 0.4 mM to a value of 6.8 ± 0.4 mM (p < 0.005).

Figure 2 shows the effect of 10\textsuperscript{-6} M norepinephrine on a\textsubscript{\text{ajv}} in the presence of 16.2 mM [K\textsuperscript{+}]\textsubscript{c}. This level of
that was lower than the control tension in Tyrode solution. This is consistent with the idea that lowering $a_{Na}^{\infty}$ plays a role in the control of contractile tension through a $Na^{+}-Ca^{2+}$ exchange. Washout of norepinephrine led to recovery of $a_{Na}^{\infty}$ to the level it had been lowered to by TTX. In the presence of TTX, norepinephrine shifted the action potential plateau to a more positive level (action potential “c” in Figure 5D), although $V_m$ only depolarized slightly. In the absence of TTX, $V_m$ slightly hyperpolarized on the exposure to norepinephrine. In both cases, however, $a_{Na}^{\infty}$ decreased and $V_m$ changes might not have played a significant role in the $a_{Na}^{\infty}$ change. After washout of TTX, $a_{Na}^{\infty}$ recovered to the control level in Tyrode solution. In 4 experiments in 4 tissues; control $a_{Na}^{\infty}$ averaged $8.5 \pm 1.3$ mM and $5 \times 10^{-6}$ M TTX lowered $a_{Na}^{\infty}$ to a mean of $7.4 \pm 1.1$ mM ($p<0.05$). Exposure to $10^{-6}$ M norepinephrine in the presence of TTX further lowered $a_{Na}^{\infty}$ by $0.9 \pm 0.2$ mM to $6.5 \pm 1.0$ mM ($p<0.005$).

The Effect of Analogues of cAMP on $a_{Na}^{\infty}$ and Twitch Tension

In cardiac Purkinje fibers the effect of norepinephrine on $a_{Na}^{\infty}$ is presumably mediated by $\beta$ receptors since propranolol blocks the response and isoprenaline mimics it. If so, this response should be mediated by cAMP. We therefore tested the effects of two analogues of cAMP, 8-ClPheScAMP and DBcAMP, on $a_{Na}^{\infty}$ and twitch tension. These analogues were used because they are more stable than cAMP itself.

Figure 6 shows the effect of $10^{-4}$ M 8-ClPheScAMP on $V_m$, $a_{Na}^{\infty}$, twitch tension (T) and action potential in a canine cardiac Purkinje fiber. As shown in Figure 6A, 8-ClPheScAMP caused a hyperpolarization of $V_m$. Although norepinephrine in the presence of TTX increased twitch tension, the tension increased to a level

$V_m$ hyperpolarized as shown in trace A. The hyperpolarization in $V_m$ was largely due to a shortening of the action potential and to a more negative plateau (action potential “b” in Figure 5D). Addition of norepinephrine in the presence of TTX caused a further fall in $a_{Na}^{\infty}$. Although norepinephrine in the presence of TTX increased twitch tension, the tension increased to a level

$V_m$ hyperpolarized as shown in trace A. The hyperpolarization in $V_m$ was largely due to a shortening of the action potential and to a more negative plateau (action potential “b” in Figure 5D). Addition of norepinephrine in the presence of TTX caused a further fall in $a_{Na}^{\infty}$. Although norepinephrine in the presence of TTX increased twitch tension, the tension increased to a level
After a delay of 3–4 minutes, twitch tension rose gradually. In this experiment no change in diastolic tension occurred; in some experiments a fall in diastolic tension was present during the increase in twitch tension. During the recovery, twitch tension fell to values below control (undershoot) (Point c in Figure 6C and twitch tension “c” in 6D). At that point, the plateau of the action potential was similar to control levels, but the action potential duration was still somewhat shortened (action potential “c” in Figure 6D). $a_{\text{Na}}$ fell slowly after a delay and recovered gradually in concert with the recovery from the undershoot of tension. Note that during the undershoot of tension, $a_{\text{Na}}$ was lower than the control $a_{\text{Na}}$ prior to the exposure to 8-ClPheScAMP. Thus, the undershoot of tension appears to be related to the low $a_{\text{Na}}$. In 25 tests in 7 tissues, exposure to $10^{-3}$ M 8-ClPheScAMP for 5–10 minutes increased twitch tension by $100 \pm 63\%$, and the largest decrease from control twitch tension during the undershoot averaged $-28 \pm 8\%$. $a_{\text{Na}}$ was measured in 18 of these tests (6 tissues) and averaged $8.4 \pm 2.7$ mM under control conditions. $a_{\text{Na}}$ fell by an average of $1.0 \pm 0.4$ mM to a value of $7.4 \pm 2.5$ mM during exposure to 8-ClPheScAMP ($p < 0.00005$).

Exposure of fibers to 2–5 mM DBcAMP for 6–10 minutes produced changes similar to those produced by 8-ClPheScAMP, although with a slightly longer time course. In 16 tests in 7 tissues the maximum increase in twitch tension was $94 \pm 67\%$, and the maximum decrease in twitch tension during the undershoot was $-23 \pm 8\%$. $a_{\text{Na}}$ was measured in 11 of these tests and averaged $7.1 \pm 1.3$ mM under control conditions and $a_{\text{Na}}$ declined by $0.9 \pm 0.3$ mM to an average minimum value of $6.2 \pm 1.2$ mM ($p < 0.00005$).

These results are qualitatively similar to those obtained with norepinephrine except that the time course of onset and recovery of the effect was slower with the cAMP analogues. In particular, the increase in twitch tension was slower to develop. We did not define a level of maximum tension (see Figure 6C), and so it is not clear if tension would have declined from a peak as it does during exposure to norepinephrine.

**Discussion**

This study is concerned with three major questions: 1) Is the decrease of $a_{\text{Na}}$ in the presence of norepinephrine due to stimulation of the Na$^+$–K$^+$ pump or is it caused by other factors such as K$^+$ accumulation in the intercellular space or a decrease in Na$^+$ influx? 2) Does cAMP mimic the effect of norepinephrine on $a_{\text{Na}}$? 3) Does the fall in $a_{\text{Na}}$ in the presence of norepinephrine play a role in the control of contractile force in cardiac Purkinje fibers? The results indicate that 1) the decrease in $a_{\text{Na}}$ is due to stimulation of the Na$^+$–K$^+$ pump by norepinephrine independent of K$^+$ accumulation in the intercellular space. A decrease in Na$^+$ influx, although difficult to dissect out, seems to play at most a minor role. 2) Stimulation of the Na$^+$–K$^+$ pump by norepinephrine is mediated through cAMP, and 3) the changes in tension during washout are consistent with a role for the decrease in $a_{\text{Na}}$ in the control of contractile force, presumably via Na$^+$–Ca$^{2+}$ exchange.

**Norepinephrine and the Na$^+$–K$^+$ Pump**

One purpose of these studies was to evaluate whether pump stimulation in the presence of catecholamines might be due to potassium accumulation in the intercellular space due to an increase in potassium conductance. $9,10$ Canine cardiac Purkinje fibers were chosen for study since their intercellular spaces are relatively less constrained in the dog than in other species. $24$ Removal of potassium from the external solution substantially inhibits the sodium pump in cardiac tissue. $25,26$ If norepinephrine caused sufficient potassium leak to elevate potassium in the intercellular space, stimulation of the sodium pump, and a fall in $a_{\text{Na}}$, or at
least in the rate of rise of \( a_{\text{Na}} \) would be expected. In our studies exposure to norepinephrine did not observably affect \( a_{\text{Na}} \) in fibers bathed in K-free solution (Figure 4). This negative result, which is similar to that reported on the effect of norepinephrine in the presence of cardiotonic steroids,\(^7\) is consistent with an effect of norepinephrine on the sodium pump, independent of potassium accumulation. However, in the presence of K-free solution, Purkinje fibers depolarize to a level of about \(-30\) mV (see Figure 2A), membrane resistance increases and K\(^+\) conductance falls.\(^22,23\) Therefore, in K-free solution, norepinephrine might not increase K\(^+\) conductance as it does in the presence of normal [K\(^+\)], although it does hyperpolarize the membrane potential (see Figure 4A).

We therefore examined the effects of norepinephrine in the presence of 16.2 mM [K\(^+\)]. This concentration causes near maximal pump stimulation achievable from elevating [K\(^+\)].\(^20,21\) Exposure to 16.2 mM [K\(^+\)] depolarizes the fiber and decreases \( a_{\text{Na}} \) from control levels. This decrease probably results from a decrease in sodium influx in the absence of action potentials, and perhaps due to effects of depolarization per se on sodium flux.\(^25\) A change in pump activity is unlikely to be an important contributor to this decrease since \( a_{\text{Na}} \) doesn’t change in voltage-clamped fibers when [K\(^+\)] is raised from 5.4 to 15 mM.\(^27\) In the setting of high [K\(^+\)], norepinephrine caused a further decline in \( a_{\text{Na}} \) (Figure 2). Further, the norepinephrine-induced decrease in \( a_{\text{Na}} \) in the setting of 16.2 mM [K\(^+\)], is blocked by strophanthidin (Figure 3), just as it is in the presence of 5.4 mM [K\(^+\)].\(^7\) These results strongly indicate that norepinephrine stimulates the sodium pump independently of an increase in K\(^+\) conductance since any potassium accumulation could not be expected to enhance sodium pump activity significantly beyond that caused by 16.2 mM [K\(^+\)].

A strong linear correlation is present between the absolute change in \( a_{\text{Na}} \) after norepinephrine and the prenorepinephrine \( a_{\text{Na}} \) for all 14 exposures in normal Tyrode, high [K\(^+\)], and TTX (\( r = 0.73, p < 0.001 \)), and this is supported by the trends present among the three groups (see Table 1). Such a correlation is compatible with the pump-leak model, assuming first-order dependence of sodium efflux on \( a_{\text{Na}} \), as has been found empirically at levels of \( a_{\text{Na}} \) in the range of these experiments.\(^21,28,29\) If norepinephrine changes the rate exchange of Na\(^+\) efflux similarly in each experimental condition without affecting influx, then in the steady state:

\[
k \cdot (a_{\text{Na}}) = k_{\text{Ne}} \cdot (a_{\text{Na},\text{Ne}}) \text{ or } k_{\text{Ne}}/k = (a_{\text{Na}})/(a_{\text{Na},\text{Ne}})
\]

where \( k \) and \( k_{\text{Ne}} \) are the rate constants of Na\(^+\) efflux in the absence and presence of norepinephrine, respectively, and \( a_{\text{Na}} \) and \( a_{\text{Na},\text{Ne}} \) are the steady-state intracellular sodium ion activities before and during exposure to norepinephrine, respectively. This model predicts that the absolute change in \( a_{\text{Na}} \) after norepinephrine should be proportional to the prenorepinephrine \( a_{\text{Na}} \), while the percent decrease and the ratio \( a_{\text{Na}}/a_{\text{Na},\text{Ne}} \) should be constants, with this ratio indicating the degree of pump stimulation. The ratios for each experimental group are shown in Table 1 and are not significantly different (\( p > 0.10 \) for each comparison). Further, the percent decrease in \( a_{\text{Na}} \) after norepinephrine for the three groups are not significant (\( p > 0.10 \) for each comparison). However, contrary to the model, the absolute decrease in \( a_{\text{Na}} \) with norepinephrine is not significantly different among the three groups (\( p > 0.10 \) for each comparison), although the trend is stronger than for the ratio or percent decrease. Thus, our data are compatible with the simplest model for the norepinephrine effect on \( a_{\text{Na}} \), a single effect on the pump (here with 10–20% stimulation by norepinephrine). Reasons for departures from the model could include scatter of the control \( a_{\text{Na}} \) levels, different degrees of pump stimulation under the different experimental circumstances or an effect on sodium influx.

**Effect of Norepinephrine on Na\(^+\) Influx**

It is possible that part of the effect of norepinephrine to lower \( a_{\text{Na}} \) derives from alterations in Na\(^+\) influx. In our experiments, TTX did not block this effect, suggesting that the fast sodium channel is not principally involved. Further, the prevention of the effect by strophanthidin in normal Tyrode’s solution,\(^7\) 16.2 mM Tyrode’s solution (Figure 2), and in the presence of TTX\(^*\) as well as by K-free solution (Figure 4) argue against a role for alterations of Na\(^+\) influx under a variety of membrane and contractile conditions. The

---

### Table 1. Ratio of \( a_{\text{Na}} \) Before Norepinephrine or Analogues of cAMP to \( a_{\text{Na}} \) During Norepinephrine Exposure (\( a_{\text{Na},\text{Ne}} \))

<table>
<thead>
<tr>
<th>Bathing solution</th>
<th>( a_{\text{Na}} ) (mM)</th>
<th>( a_{\text{Na},\text{Ne}} ) (mM)</th>
<th>( a_{\text{Na}}/a_{\text{Na},\text{Ne}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyrode</td>
<td>8.0 ± 0.4</td>
<td>6.8 ± 0.4</td>
<td>1.19 ± 0.06</td>
</tr>
<tr>
<td>16.2 mM K Tyrode</td>
<td>6.5 ± 0.5*</td>
<td>5.9 ± 0.2</td>
<td>1.11 ± 0.06</td>
</tr>
<tr>
<td>Tyrode plus TTX</td>
<td>7.4 ± 1.1</td>
<td>6.5 ± 1.0</td>
<td>1.15 ± 0.03</td>
</tr>
<tr>
<td>Tyrode</td>
<td>8.4 ± 2.7</td>
<td>7.4 ± 2.5</td>
<td>1.15 ± 0.08</td>
</tr>
<tr>
<td>Tyrode</td>
<td>7.1 ± 1.3</td>
<td>6.2 ± 1.2</td>
<td>1.15 ± 0.06</td>
</tr>
</tbody>
</table>

All data are expressed as mean ± SD. Number of experiments are indicated in text. *\( p < 0.01 \) in comparison with \( a_{\text{Na}} \) in Tyrode solution.
finding that apparent pump stimulation by norepinephrine (a\text{a}_2/a\text{a}_1) is similar under different conditions is also in keeping with this hypothesis. Thus, although norepinephrine may have direct or indirect effects on Na\textsuperscript{+} influx, they do not play a major part in the observed changes in a\text{a}_2.

**Analogues of cAMP and the Na\textsuperscript{+}-K\textsuperscript{+} Pump**

Our results with 8-ClPheScAMP and DBCAMP show that these agents mimic the effects of norepinephrine in several important aspects. First, analogues of cAMP cause both positive and negative inotropic effects. The positive inotropic effects occur more slowly than those due to norepinephrine. The negative inotropic effects are unmasked during washout of the agent. Second, both norepinephrine and the cAMP analogues affect the action potential in a similar way — elevating the plateau and shortening the duration. Despite substantial shortening of action potential duration during norepinephrine and 8-ClPheScAMP exposure, twitch tension increased to more than twice control levels (Figures 1 and 6). During the undershoot of twitch tension, action potential duration was slightly shortened compared to control. It is not clear how the changes in action potential duration contributed to the changes in tension. Third, both agents lower a\text{a}_2 and the recovery of a\text{a}_2 parallels the recovery of twitch tension from the undershoot (Figure 1B, C and 6B, C).

Further, the degree of pump stimulation as judged by the ratio of a\text{a}_2 before administration of the cAMP analogue to that after administration is similar to that due to norepinephrine (see Table 1). There are differences between the time courses of the effects of norepinephrine and of the cAMP analogues, the effects of the former being more rapid. These are most likely related to the pharmacologic properties of the agents, lack of precise dose equivalence, and the speed with which the cAMP analogues enter cells.

In skeletal muscle, norepinephrine’s effects on sodium and potassium transport are mediated via β\textsubscript{2} receptors. Similarly, the effects of β agonists to lower extracellular potassium concentration in animals and in man are also β\textsubscript{2} mediated. Our results, which show that analogues of cAMP stimulate the sodium pump, indicate that, since β\textsubscript{2} agonists stimulate cAMP production in heart muscle, one need not invoke a β\textsubscript{2} effect to explain the changes in monovalent cation transport induced by norepinephrine.

**Norepinephrine, Na\textsuperscript{+}-K\textsuperscript{+} Pump, and Contractile Force**

Both norepinephrine and analogue of cAMP produced positive and negative inotropic effects on cardiac Purkinje fibers (Figures 1 and 6). Norepinephrine has dual effects on contractility. It increases the calcium conductance and the slow inward current, which elevates the plateau. The ensuing increase in intracellular calcium leads to a positive inotropic effect. At the same time, with a slower time course, norepinephrine stimulates the sodium pump, lowering a\text{a}_2. The decrease in a\text{a}_2 and concomitant increase in the inward sodium gradient exerts a powerful effect on contractility through Na\textsuperscript{+}-Ca\textsuperscript{2+} exchange. This occurs by causing a sodium–calcium exchange to either increase calcium efflux or decrease calcium influx, or both. This decrease in cellular calcium would lead to a negative inotropic effect. The net effect of norepinephrine on twitch tension would depend on a balance between these two opposing actions. The effect on the calcium conductance would seem to develop more rapidly than the negative inotropic effect mediated by the sodium pump. The present results indicate that it is likely that both of these effects are mediated by cAMP.

**References**

7. Lee CO, Vassalle M: Modulation of intracellular Na\textsuperscript{+} activity and cardiac force by norepinephrine and Ca\textsuperscript{2+}. *Am J Physiol* 1983;244:C110–C114
13. Im W-B, Pecker MS, Lee CO: Effects of (K\textsuperscript{+}) and norepinephrine on intracellular sodium ion activity and twitch tension of canine cardiac Purkinje fibres (abstract). *Biophys J* 1983;41:308A
15. Lee CO, Dagostino M: Effect of strophantidin on intracellular
Pecker et al  Norepinephrine and Na\textsuperscript{+}–K\textsuperscript{+} Pump

Na ion activity and twitch tension of constantly driven canine cardiac Purkinje fibers. Biophys J 1982;40:185–198


20. Gadsby DC: Activation of electrogenic Na\textsuperscript{+}/K\textsuperscript{+} exchange by extracellular K\textsuperscript{+} in canine Purkinje fibers. Proc Natl Acad Sci USA 1980;77:4035–4039

21. Gadsby DC, Cranefield PF: Two levels of resting potential in cardiac Purkinje fibers. J Gen Physiol 1977;70:725–746


34. Sheu SS, Fozzard HA: Transmembrane Na\textsuperscript{+} and Ca\textsuperscript{2+} electrical gradients in cardiac muscle and their relationship to force development. J Gen Physiol 1982;80:325–351


KEY WORDS • norepinephrine • adenosine 3':5'-cyclic monophosphate • intracellular Na\textsuperscript{+} ion activity • Na\textsuperscript{+}–K\textsuperscript{+} pump • contractile force • canine cardiac Purkinje fibers
Effect of norepinephrine and cyclic AMP on intracellular sodium ion activity and contractile force in canine cardiac Purkinje fibers.

M S Pecker, W B Im, J K Sonn and C O Lee

Circ Res. 1986;59:390-397
doi: 10.1161/01.RES.59.4.390

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/59/4/390