The Combined Effects of Hypoxia, High K⁺, and Acidosis on the Intracellular Sodium Activity and Resting Potential in Guinea Pig Papillary Muscle

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SUMMARY. Several reports have shown that electrical and ionic changes occurring in acute myocardial ischemia can be closely mimicked by exposure of tissue to hypoxic, acid-, and glucose-free solutions at elevated [K⁺]₀. In the present work, this approach was chosen to distinguish between the combined effects of hypoxia, substrate withdrawal, and acidosis, and the effects of two different levels of [K⁺]₀ (4.7 mM and 11.5 mM) on intracellular sodium activity and resting membrane potential. Measurements were made with microelectrodes in isolated guinea pig papillary muscles. In normoxia at 4.7 mM [K⁺]₀, intracellular sodium activity was 7.5 mM (±1.9 mM, SD) during stimulation at 1 Hz. Combined hypoxia, substrate withdrawal, and acidosis increased intracellular sodium activity significantly, by 3—4 mM in 4.7 mM [K⁺]₀ and by approximately 2 mM in 11.5 mM [K⁺]₀, after 9—10 minutes. Increasing [K⁺]₀ in normoxic solution decreased intracellular sodium activity by 1.9 mM (±1.3 mM, SD). The transition from normal (4.7 mM [K⁺]₀) Tyrode’s solution to “ischemic solution” (hypoxia, acidosis, substrate withdrawal, 11.5 mM [K⁺]₀) was associated with a small initial increase and a subsequent decrease of intracellular sodium activity. The steady state level after 12 minutes was not significantly different from the level in normal Tyrode’s solution. The secondary decrease of intracellular sodium in early ischemia results from two opposing changes: (1) a partial inhibition of the sodium-potassium pump by hypoxia, glucose-withdrawal, and acidosis, and (2) a decrease of passive sodium influx following extracellular potassium accumulation in the restricted extracellular space. Our results suggest that alteration of intracellular sodium in myocardial ischemia results from two opposing changes: (1) a partial inhibition of the sodium-potassium pump by hypoxia, glucose-withdrawal, and acidosis, and (2) a decrease of passive sodium influx following extracellular potassium accumulation. Moreover, the present results support previous findings that net cellular potassium loss from ischemic cells is not (fully) compensated by an equivalent gain of intracellular sodium. (Circ Res 58: 249—256, 1986)

MYOCARDIAL ischemia and hypoxia are associated with rapid changes of membrane potential (see Janse and Kléber, 1981), passive electrical properties (Wojtczak, 1979), and ionic shifts between the intracellular and extracellular space (see Kléber, 1984). A rapid extracellular accumulation of K⁺ follows the arrest of myocardial blood supply (Hill and Gettes, 1980). It has been suggested that net K⁺ loss from cells in both ischemia and hypoxia is the result of an imbalance between an increased efflux and a maintained active K⁺ influx, i.e., active Na⁺/K⁺ pumping (Vleugels and Carmeliet, 1976; Rau et al., 1977; Weiss and Shine, 1982; Kléber, 1983). Recently, the idea of at least partially maintained Na⁺/K⁺ pump activity was supported by the finding of an unchanged intracellular sodium in early ischemia (Klèber, 1983). Several other experimental reports have suggested that active Na⁺/K⁺ transport may have been impaired by oxygen withdrawal. First, an increase of intracellular sodium, as determined by a washout method, was measured in early hypoxia of the rat heart (Fiolet et al., 1984). Second, a small but significant decrease in Na⁺/K⁺ adenosine triphosphatase (ATPase) activity was observed in isolated sarcolemmal vesicles from ischemic rabbit heart (Bersohn et al., 1982). Third, the supply of chemical energy, as represented by the free energy available from adenosine triphosphate (ATP) hydrolysis, undergoes a marked decrease in acute hypoxia and ischemia (Kammermeier et al., 1982; Fiolet et al., 1984).

In the steady state, intracellular sodium will be determined primarily by the balance between passive Na⁺ influx and active Na⁺ pumping. Thus, a decrease of membrane potential, and, consequently, of Na⁺ influx, results in a decrease of sodium activity in normoxic tissue (Eisner et al., 1981; January and Fozzard, 1984). Therefore, a decrease of Na⁺ influx in early ischemia, resulting from the marked decrease in resting potential (Klèber, 1984), might mask an eventual partial inhibition of the Na⁺/K⁺ pump.

We carried out the present experiments to investigate the effect of hypoxia and acidosis at normal and elevated extracellular potassium concentration [K⁺]₀ on intracellular Na⁺ activity in guinea pig...
papillary muscle. It has been shown that the combination of elevated [K+]o, hypoxia, and acidosis closely imitates the changes of membrane potential (Moréna et al., 1980) and of impulse conduction (Kagiyama et al., 1982) observed in myocardial ischemia. Under these experimental conditions, it proved possible (for the first time) to maintain two simultaneous intracellular electrode impalements over a relatively long period of time in a beating papillary muscle and, thus, to assess relatively small changes of intracellular Na⁺ activity under different experimental conditions.

**Methods**

**Preparations, Recording Chamber, and Solutions**

Guinea pigs (body weight, 300–400 g) were killed by a blow to the head. The heart was rapidly removed and placed in a preparation chamber, where papillary muscles less than 4–5 mm long and less than 1 mm in diameter were excised from the right ventricle. Occasionally, muscles also were taken from the left ventricle and split longitudinally, forming a strip of the same diameter as the intact preparations from the right ventricle.

The Perspex recording chamber consisted of three compartments separated by two rubber membranes. The mid-compartment (width, 1 mm) was perfused with isotonic sucrose solution containing 10⁻³ M Ca⁺⁺ (Kleber, 1973). The left compartment contained isotonic KCl solution, and the right compartment was perfused with the test solution. The papillary muscle was introduced through holes in the two rubber membranes, with the apex of the preparation in the test compartment. Normally, the length protruding into the test compartment was 1.5–2 mm. For stimulation, rectangular 1.0-msec current pulses were applied between the left compartment (cathode) and the test compartment (anode, electrical ground) at double threshold strength. The sucrose gap arrangement was chosen in order to obtain close to simultaneous excitation of the cells in the test compartment. If the current threshold increased during an experimental intervention (at elevated [K+]o with or without hypoxia), stimulus current strength was increased up to a maximum of four times the initial value. The experimental temperature was kept between 36°C and 37°C. During superfusion at normal P O₂, two different test solutions were used: (1) Tyrode’s solution at normal pH (7.4) and with normal [K+]o (4.7 mm), and (2) Tyrode’s solution at normal pH and with elevated [K+]o (11.5 mm). During exposure to hypoxia, three different test solutions were used, all with a low pH (mean 6.77, see below): (1) Tyrode’s solution with normal [K+]o, (2) glucose-free Tyrode’s solution with normal [K+]o, and (3) glucose-free Tyrode’s solution with elevated [K+]o (11.5 mm). The composition of normal Tyrode’s solution was as follows (in mM): Na⁺, 153.5; K⁺, 4.7; Ca⁴⁺, 1.3; Mg²⁺, 0.6; Cl⁻, 136.5; HCO₃⁻, 25; H₂PO₄⁻, HPO₄⁻, 0.4; glucose, 20. In the solution containing 11.5 mm K⁺, the Na⁺ was reduced by 6.8 mm. This small reduction will cause a decrease of a D by approximately 5% (Chapman et al., 1983), and effect which was neglected in our experiments. To obtain normoxic conditions and normal pH, gassed the solutions with a constant mixture of 95% O₂ and 5% CO₂ (Carba Gas, Switzerland) at 37°C. Hypoxia and acidosis were achieved by equilibrating the solutions with a mixture of N₂ and CO₂. The volume fraction of CO₂ in this mixture was adjusted to yield a pH of 6.77 (±0.05, so, n = 31). All connections between the glassware used for storage of the solutions and the recording chamber were made of stainless steel to prevent gas exchange between the virtually O₂-free test solutions and the surrounding atmosphere. In this way, a P O₂ <5 mm Hg was obtained in the recording chamber, as measured by an O₂ microelectrode (J. Streit, unpublished data).

**Measurement of Intracellular Na⁺ Activity and Membrane Potential**

Intracellular sodium activity (a D) was measured by microelectrodes (borosilicate glass) filled with the neutral Na⁺ carrier ETH 227 (Steiner et al., 1979). Several reports have described the fabrication and calibration procedure of such Na⁺-sensitive microelectrodes (e.g., Chapman et al., 1983). The details of the preamplifiers and amplifiers used to process the microelectrode signals were given in an earlier report (Kleber, 1983).

In the test compartment, each papillary muscle was impaled by a conventional microelectrode and a Na⁺-sensitive microelectrode (interelectrode distance, <0.8 mm). The distance from the sucrose compartment was chosen to be greater than 1 mm to avoid the effects of sucrose diffusion into the test compartment (Kleber, 1973). Both potentials recorded from each electrode (conventional microelectrode, V M; Na⁺-sensitive electrode, V Na) were referred to the potential of a third microelectrode placed in the superfusing solution close to the impaling sites. Calibration curves relating V M = V Na to a D were obtained before and after an experiment (at 34–36°C) using the calibration chamber described by Weingart and Hess (1984). For calculation of a D, an activity coefficient of 0.764 was used (Bates et al., 1970). In the calibration solutions, the sum of Na⁺ and K⁺ was always 151.1 mm. The solutions contained in addition 3 mM Mg²⁺, 5 mM HEPES at a pH of 7.0 and Cl⁻. The selectivity of the neutral Na⁺ carrier, ETH 227, and interference from K⁺ and Ca⁴⁺ have been discussed previously, e.g., by Cohen et al. (1982) and by Vasalle and Lee (1984). In the present experiments, increased K⁺ efflux during hypoxia (Vleugels and Carmeliet, 1976; Rau et al., 1977) and the consequent decrease of a D (Wier, 1978) might have changed the potential recorded by the Na⁺ electrode. At a selectivity coefficient K⁺-Na⁺ of 0.01 to 0.02 (e.g., Dagostino and Lee, 1982), an assumed decrease of a D from a normal value of 100 mm (Wier, 1978; Baumgarten et al., 1981) by one-third would mimic a decrease of a D by 0.3–0.6 mm. Therefore, this small source of interference was ignored in the analysis of the data.

A pen recorder (Watanabe mark VII) served for recording of V M = V Na and V Na-V M. To obtain V Na-V M, V Na and V M were filtered by two low-pass filters (corner frequency, 0.1 Hz) before subtraction (Lee and Dagostino, 1982; Vassalle and Lee, 1984). A single papillary muscle was subjected to a maximum of three hypoxic periods lasting no longer than 15 minutes. After these hypoxic periods, changes of a D and V M were always reversible. When longer periods were studied, the preparations were not used for further measurements. Only those experiments during which both impalements remained stable before and during a certain intervention were taken for analysis. In most cases, both electrodes were withdrawn into the bulk solution after a measurement, and were reimpaled before reexposure to a test solution. In the original recordings of V Na-V M shown in Results, the voltage scale (in mV) has been converted to a D (in mm). The summarized values of V M, ΔV M, a D, Δa D, and pH are
expressed as mean ± sd. Statistical comparison of V_M and a_Na values before and during an experimental intervention was made by the paired samples t-test.

Homogeneity of Resting Potential

Theoretically, the potential error introduced by the measurement of V_M and V_MN with separate electrodes in different cells might become important during hypoxia: this is because the electronic interaction between neighboring cells will probably decrease as a consequence of an increase in internal longitudinal resistance (Wojtczak, 1979) and an increase in membrane conductance (Vleugels et al., 1980). Therefore, the problem of homogeneity of V_M was addressed in two papillary muscles (three measurements) by the simultaneous impalement with two electrodes (V_{Mi}, V_{M2}), as illustrated in Figure 1. This figure shows the membrane potentials during continuous impalements (top and middle tracings) of two intracellular electrodes situated 0.8 mm apart. The bottom trace depicts the differential voltage V_{M2}-V_{Mi}. During the 11-minute period indicated by the bar from 1 to 2, the fiber was exposed to hypoxic, glucose-free solution at low pH; during the period 2 to 3, it was superfused with normoxic Tyrode’s solution at a K^* of 11.5 mM. After a period of exposure to normal Tyrode’s solution, the two electrodes were withdrawn into the extracellular space (arrow).

During both interventions, V_{Mi} and V_{M2} decreased by the same amount and produced no change in the differential tracing V_{M2}-V_{Mi}. Upon withdrawal, the difference between V_{Mi} (—86 mV) and V_{M2} (—84.5 mV) caused a shift of V_{M2}-V_{Mi} by —1.5 mV. In all three control measurements, no change of V_{M2}-V_{Mi} was observed during exposure to hypoxic solutions, whereas the shift upon withdrawal amounted to —1.5 mV, 0 mV, and 1 mV, respectively. This indicates the order of magnitude of differences in tip potential or resting potential which can affect the measurement of a_Na in a random fashion. However, interventions such as exposure to hypoxic or “high [K^*]_o” solutions will not introduce additional inhomogeneity of resting potential or variability in the measurement of a_Na.

Results

Effects of Hypoxia and Acidosis on Membrane Potential and Intracellular Sodium

Mean a_Na in 15 different muscles amounted to 7.5 mM (±1.9 mM, 33 impalements) during normoxic perfusion at [K^*]_o of 4.7 mM and at a stimulation frequency of 1 Hz. Under the same conditions, a mean resting potential of —83.4 mV (±3.6 mV; n = 33) was obtained.

The effect of hypoxic, glucose-free and acidic solutions ([K^*]_o of 4.7 mM and at a stimulation frequency of 1 Hz) on membrane potential and intracellular sodium activity in a single experiment is shown in Figure 2. Intracellular Na^+ activity increased from an initial level of 5.1 mM to a plateau level within 10 minutes, which, on average, was 5 mM higher than the control level. Resting potential decreased with a similar time course from —86 mV to a new level of —80 mV. The changes of resting potential (∆V_M) and intracellular sodium activity (∆a_Na) expressed as mean values with standard deviations from six experiments (in six different preparations) are depicted in Figure 3 and listed in Table 1. All preparations were paced at 1 Hz. Resting membrane potential depolarized to a steady level after 11 minutes, which was 8.3 mV (±4.5 mV) less negative than the resting potential in normal Tyrode’s solution. In none of the experiments was spontaneous diastolic depolarization observed. The loss of resting potential was statistically significant (P < 0.05) between 2 and 15 minutes of exposure to hypoxic, acidic, and glucose-free medium. Intracellular Na^+ activity started to increase within the first 2 minutes after the change of the superfusate. The increase of a_Na reached a peak between 10 and 12 minutes (3.5 ± 2.7 mM at 10 minutes). Subsequently, a secondary minor decline occurred to values 2.5—3 mM above the control level (statistical significance (P < 0.05) was obtained for values between 6 and 14 minutes and between 22 and 30 minutes). It is not clear whether this secondary decrease was of biological relevance or whether it reflected random variation. It was not related to a change in amplitude or maximum upstroke velocity of the action potential.

In six additional experiments (five different preparations), the changes of V_M and a_Na were recorded after exposure to hypoxic, acidic Tyrode’s solution which contained 20 mM glucose (Table 1). The
TABLE 1  Changes of Membrane Potential (AVM) and Intracellular Sodium Activity (AaNa)

<table>
<thead>
<tr>
<th>Control solution</th>
<th>Test solution</th>
<th>Rate (Hz)</th>
<th>n</th>
<th>V_M (mV)</th>
<th>AaNa (mM)</th>
<th>ΔV_M (mV)</th>
<th>ΔAaNa (mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Tyrode</td>
<td>Hypoxia, acidosis, no glucose, 4.7 mM [K+]</td>
<td>1</td>
<td>6</td>
<td>82.8 ± 3.8</td>
<td>6.2 ± 1.8</td>
<td>8.3 ± 4.5*</td>
<td>3.5 ± 2.7*</td>
</tr>
<tr>
<td>Normal Tyrode</td>
<td>Hypoxia, acidosis, 20 mM glucose, 4.7 mM [K+]</td>
<td>1</td>
<td>5</td>
<td>78.8 ± 1.9</td>
<td>7.6 ± 0.7</td>
<td>9.0 ± 3.3*</td>
<td>1.6 ± 1.0*</td>
</tr>
<tr>
<td>Normal Tyrode</td>
<td>Hypoxia, acidosis, no glucose, 11.5 mM [K+]</td>
<td>1</td>
<td>5</td>
<td>59.2 ± 2.6</td>
<td>3.8 ± 1.4</td>
<td>7.3 ± 2.3*</td>
<td>2.2 ± 1.3*</td>
</tr>
<tr>
<td>Normal Tyrode</td>
<td>Hypoxia, acidosis, no glucose, 11.5 mM [K+]</td>
<td>1</td>
<td>8</td>
<td>85.1 ± 3.2</td>
<td>7.9 ± 1.6</td>
<td>26.8 ± 1.7*</td>
<td>-0.9 ± 1.6</td>
</tr>
<tr>
<td>Normal Tyrode</td>
<td>Normal Tyrode, 11.5 mM [K+]</td>
<td>1</td>
<td>8</td>
<td>81.4 ± 3.0</td>
<td>6.9 ± 1.8</td>
<td>19.5 ± 3.3*</td>
<td>-1.9 ± 1.3*</td>
</tr>
</tbody>
</table>

Results are expressed as mean ± SD. Tyrode = Tyrode's solution.
* Denotes statistical significance of changes in AaNa and V_M (P < 0.05).

Changes of resting potential showed the same time course and were of the same magnitude as those obtained in the absence of glucose (see Fig. 3). Thus, V_M depolarized by 9.0 mV (±3.3 mV) after 10 minutes. In contrast to the similarity of the changes in resting potential, only a small increase of intracellular sodium was observed (1.6 ± 1.0 mM after 11 minutes, P < 0.05). The time course of ΔAaNa was similar to that observed in the absence of glucose, i.e., ΔAaNa reached a plateau after 10 minutes.

Effect of Elevated Extracellular Potassium on Intracellular Sodium during Hypoxia and Acidosis

Elevation of extracellular K+ is known to decrease resting potential and to reduce intracellular sodium activity (Eisner et al., 1981; January and Fozzard, 1984). During early myocardial ischemia, an accumulation of extracellular potassium by approximately 12-15 mM and a concomitant decrease of resting potential by about 30 mV takes place within the first 10 minutes after cessation of perfusion (Kléber, 1983).

To assess the combined effects of hypoxia, acidosis, and glucose-withdrawal on V_M and AaNa at elevated [K+]o, we exposed papillary muscles first to normal Tyrode's solution containing 11.5 mM [K+]o. Subsequently, we changed the superfusion to the hypoxic, acidic, and glucose-free medium at the same elevated [K+]o. Changes in test solution (9-11 min exposure) from 4.7 to 11.5 mM (time 1) was accompanied by the expected depolarization from −80 mV to −62 mV and by the decrease of AaNa from 5.8 to 2.8 mM. At time 2, the preparation was superfused for 9 minutes with hypoxic, glucose-free, and acidic solution at the same [K+]o. This caused an additional depolarization of V_M to −56 mV. In contrast, intracellular sodium activity increased from 2.8 to 4.8 mM, i.e., to slightly below the control level in normal Tyrode's solution. Subsequent exposure to normoxic Tyrode's solution containing 4.7 mM [K+]o was followed by the return of V_M and AaNa to their initial values. The mean changes of AaNa and V_M obtained in five experiments, caused by hypoxia, glucose withdrawal, and acidosis at a [K+]o of 11.5 mM, are shown in Figure 5 and in Table 1. Resting membrane potential became more positive, and AaNa increased significantly during the 9-

![Figure 3](http://circres.ahajournals.org/) Exposure to hypoxia, acidosis, and absence of glucose ([K+]o = 4.7). Mean values and standard deviations of n measurements (upper horizontal bar) of changes in resting membrane potential (ΔV_M) and intracellular sodium activity (ΔAaNa). Stimulation at 1 Hz. For further details, see text.
minute period. After 9 minutes, \( \Delta V_M \) averaged 7.3 ± 2.3 mV and \( \Delta a_{Na} \) was 2.2 ± 1.3 mM. The results shown in Figures 3 and 5 indicate that induction of hypoxia and acidosis is followed by a reduction of resting membrane potential and an increase of intracellular sodium activity, both at extracellular [K+] of 4.7 mM and 11.5 mM.

In ischemia, potassium accumulation develops within the first minutes after interruption of coronary flow. In order to mimic the transition from normoxic to ischemic conditions, we changed superfusion from normal Tyrode's solution ([K+]o, 4.7 mM) to hypoxic, acidic, and glucose-free solution containing 11.5 mM K+ ("ischemic Tyrode") for 11 minutes. Between times 1 and 2, resting potential decreased from ~87 mV to ~60 mV. Intracellular Na+ activity increased initially from 6.5 mM to 7.5 mM after 6 minutes. The occurrence of small amplitude potentials was associated with a secondary decrease of \( a_{Na} \) to 6.2 mM. Between time marks 2 and 3, the preparation was exposed to normoxic Tyrode's solution at a [K+] of 11.5 mM. This resulted in a slight hyperpolarization. At time 3, the papillary muscle was reexposed to normal Tyrode's solution.

Excitation. Finally, after a short intermittent period of electrical alternans, small local potentials remained after stimulation, which gradually underwent a further reduction in amplitude. In this type of experiment, intracellular Na+ activity showed only very small changes which were consistently biphasic. Thus, initially, \( a_{Na} \) increased by 1 mM. When the cells had lost all-or-nothing activity, a small secondary decrease was observed. The final level reached after 11 minutes of exposure to "ischemic solution" (6.2 mM) was close to the level in normal Tyrode's solution (6.5 mM). At time 2, the superfusate was changed to normal Tyrode's solution without changing [K+]o. This caused a hyperpolarization by ~4 mV, and a small and delayed decrease of \( a_{Na} \) to 5 mM. At time 3, [K+]o was lowered to 4.7 mM with consequent resumption of the original \( V_M \) and \( a_{Na} \) values.

The results of eight experiments (four preparations) in which \( \Delta a_{Na} \) and \( \Delta V_M \) were recorded after a change from normal Tyrode's solution (4.7 mM [K+]o) to hypoxic, acidic, and glucose-free medium at a [K+]o of 11.5 mM are presented in Figure 7 (square symbols) and in Table 1. For comparison, they are superimposed on the changes of resting membrane potential and intracellular Na+ activity caused by elevation of extracellular [K+] alone, and the subsequent return to normal Tyrode's solution (circles, eight experiments in 10 preparations; see also Table 1). In both types of experiments, the preparations were stimulated at 1 Hz. Resting potential in the hypoxic condition declined to a level which was 7.0–7.5 mV more positive than in normoxic Tyrode's solution at a [K+]o of 11.5 mM. Intracellular Na+ activity decreased, as expected, as a consequence of the elevation of extracellular K+ alone. The decrease amounted to 1.9 ± 1.3 mM (Table 1). Intracellular Na+ activity during exposure to "ischemic" solution showed a biphasic time course. After an initial small increase of about 1 mM
within 4-5 minutes, a secondary decrease to a steady level occurred which was 0.9 mm (±1.6 mm) below the initial level in normal Tyrode’s solution. This final aNa level (reached after 12 minutes in "ischemic" solution) was not significantly different from the level in normal Tyrode’s solution. The small biphasic change was probably real, although it was not statistically significant. This was suggested from the coincidence of occurrence of small amplitude potentials (average time 3.8 minutes, Figure 7) with the onset of the secondary decrease of aNa. After the transition from activity (1 Hz) to quiescence, a decrease of Na+ influx and, hence, of aNa is to be expected (Deitmer and Ellis, 1980; Cohen et al., 1982; Lee and Dagostino, 1982). Such an effect was regarded as important, because the gradual development of inexcitability, as shown, for example, in Figure 6, also occurs in the first minutes of the normoxic, high-K+ exposure (circles). After exposure to the "ischemic" solution, the preparations were superfused with normoxic Tyrode’s solution containing 11.5 mM [K+]o (see e.g., Fig. 6). Subsequent reexposure to normal Tyrode’s solution containing 4.7 mM K+ showed the reversibility of the changes in aNa and VNa (last square symbols after interrupted line).

**Discussion**

**Effect of Hypoxia, Acidosis, and Extracellular K+ on Intracellular Sodium Activity**

In papillary muscles stimulated at 1 Hz and exposed to normal Tyrode’s solution, intracellular Na+ activity was found to be 7.5 mm (±1.9 mm). This value compares closely to previous measurements in cardiac Purkinje fibers (Glitsch and Pusch, 1980; Cohen et al., 1982; Sheu and Fozzard, 1982; Vassalle and Lee, 1984) and in isolated cardiac muscle (Cohen et al., 1982; Sheu and Fozzard, 1982; Chapman et al., 1983).

The main purpose of this study was to investigate the effects of hypoxia, acidosis, and glucose withdrawal on aNa at normal and elevated [K+]o. These conditions were chosen because it has been shown that the changes of resting potential and action potential measured in ischemic hearts (Downar et al., 1977) can be mimicked closely by adding K+ to a hypoxic, acidic, and glucose-free perfusate (Moréna et al., 1980). This analogy is not surprising, because both accumulation of extracellular K+ (Hill and ettes, 1980) and tissue acidification (Garlick et al., 1979) take place in early ischemia, in addition to oxygen and substrate withdrawal.

The level of intracellular Na+ is determined primarily by the balance between passive Na+ influx and active Na+ efflux, the latter mediated predominantly by the Na+/K+ pump. At a constant [K+]o of 4.7 mM, the effect of hypoxia and acidosis (in the absence of glucose) was to increase aNa by 3-4 mM; this plateau level was reached within 10 minutes. The most probable explanation for this shift is a reduction in the activity of the sodium pump. Several reports are in favor of this hypothesis. (1) A reduction of Na+/K+-ATPase activity by 25% after 30 minutes of ischemia has been demonstrated by Bersohn et al. (1982) in sarcolemmal vesicles from rabbit myocardium. (2) The free energy change for hydrolysis of ATP, which provides the chemical driving force for phosphorylation of the Na+/K+-ATPase, decreases in the first 10 minutes (Kammermeier et al., 1982; Fiolet et al., 1984) with a time course similar to the change in aNa in our experiments. In part, this decrease is due to a change of inorganic phosphate (P) which accumulates 3-fold and reaches a plateau after 4 minutes in hypoxic ferret ventricle (Allen et al., 1985). In erythrocytes, an increase of P reduces the rate of sodium pumping without affecting the affinity relation between internal Na+ and the Na+/K+ pump (Garay and Garrahan, 1975).

Complete inhibition of Na+/K+ pumping by withdrawal of extracellular K+ or application of ouabain (Ellis, 1977; Eisner and Lederer, 1979) is followed
by an increase of $a_{Na}^\infty$ up to levels ranging from 15-20 mM. In addition to the present results, which show a significantly smaller increase of $a_{Na}^\infty$, studies on extracellular $K^+$ accumulation during early ischemia (Weiss and Shine, 1982; Kléber, 1983) have provided evidence that inhibition of the Na$^+$/K$^+$ pump cannot be complete. Qualitatively, the persistence of Na$^+$/K$^+$ pumping was demonstrated in those studies by a transient extracellular $K^+$ depletion upon a sudden decrease in stimulation rate. This effect was prevented by the application of a cardiac steroid (Klèber, 1983).

The present results indicate that, during exposure to hypoxia and acidosis, $a_{Na}^\infty$ is also modified by changes in Na$^+$ influx. Theoretically, this may involve several mechanisms: (1) a change in Na$^+$ permeability ($P_{Na}$) of the sarcolemmal membrane, (2) Na$^+$/Ca$^{2+}$ or Na$^+$/H$^+$ exchange, (3) changes in membrane potential with consequent changes of the electrochemical gradient for Na$^+$, and (4) rate-dependent changes of Na$^+$ influx. At present, no experimental evidence for changes of $P_{Na}$ after O$_2$ withdrawal is available. Acidosis per se was reported to decrease Na$^+$ influx in nerve (Bass and Moore, 1983). An increase of Na$^+$ entry in exchange for Ca$^{2+}$ or H$^+$ extrusion may occur. However, no detectable rise in intracellular free [Ca$^{2+}$] was found in early hypoxia (Allen and Orchard, 1984), and the increase in intracellular free [H$^+$] is too small (Allen et al., 1985) to explain a detectable increase in $[Na^+]_o$. However, $a_{Na}^\infty$ in the present report was modified by changes of membrane potential. The decrease of $a_{Na}^\infty$ upon increasing $[K^+]_o$ probably was caused by reduction of Na$^+$ influx consequent to a decrease in the electrochemical driving force for Na$^+$ in the resting cell, and by a partial inactivation of Na$^+$ channels, thereby decreasing Na$^+$ influx during action potentials. Within the range of $[K^+]_o$ tested, modulation of Na$^+$/K$^+$ pumping (i.e., Na$^+$ efflux) by changes in $[K^+]_o$ is expected to play a minor role (for discussion, see e.g., January and Fozzard, 1984). In addition to the above effect of elevated $[K^+]_o$ per se (Fig. 7), the combination of high $[K^+]_o$, hypoxia, acidosis, and the absence of glucose leads to a gradual development of inexcitability (e.g., Fig. 6) which is associated with a decrease of $a_{Na}^\infty$. The same phenomenon is regularly observed between 4 and 7 minutes of acute myocardial ischemia (e.g., Downar et al., 1977). This may be regarded as equivalent to the transition from a stimulated to a quiescent fiber. The levels of internal sodium which accompany the transition from normal to "ischemic" Tyrode's solution was associated with a reduction of $V_M$ which was significantly greater than the reduction caused by elevation of $[K^+]_o$ from 4.7 to 11.5 mM in normal Tyrode's solution (Fig. 7). Net cellular $K^+$ loss, which most likely was the cause of this extra- depolarization, occurred without a concomitant increase of $a_{Na}^\infty$. The mechanism of net $K^+$ efflux and the identity of the ions which account for electroneutrality remain to be elucidated (see Kléber, 1984).

Effect of Hypoxia and Acidosis on Resting Membrane Potential

In both myocardial ischemia and hypoxia, changes of resting membrane potential ($V_M$) closely follow the changes of potassium equilibrium potential ($E_K$ (Baumgarten et al., 1981; Guarnieri and Strauss, 1982; Kléber, 1983)). In hypoxic muscle, a decrease of intracellular $K^+$ activity from 99-86 mM has been reported after 2 hours of hypoxic super- fusion (Wier, 1978). At later stages, a more pronounced decrease of intracellular $K^+$ activity occurs (Baumgarten et al., 1981; Guarnieri and Strauss, 1982). In the early stage of hypoxia, intracellular $K^+$ depletion results from an increase of $K^+$ influx (Vleugels and Carmeliet, 1976; Rau et al., 1977). In the case of myocardial ischemia, where no washout of $K^+$ from the extracellular space can take place, a marked increase in $[K^+]_o$ has been reported (e.g., Hill and Gettes, 1980). Our present results suggest that the depolarization which develops after exposure to hypoxia and acidosis at either $[K^+]_o = 4.7$ mM or 11.5 mM in the bulk solution was related to extracellular $K^+$ accumulation in the restricted extracellular fiber space, in addition to loss of intracellular $K^+$. Estimation of intracellular potassium activity from the observed membrane potential and from $[K^+]_i$ in the superfuse (by means of the Nernst equation) yields values that are considerably lower than the 86 mM found by Wier (1978) after 2 hours of exposure to hypoxia. This indicates that the extracellular $[K^+]$ which effectively contributes to the level of resting potential was higher than in the bulk solution.

Our results confirm indirectly that cellular $K^+$ loss in myocardial ischemia is not fully compensated by an equivalent gain of intracellular Na$^+$ (Klèber, 1983). This is suggested from the observation that the transition from normal to "ischemic" Tyrode's solution was associated with a reduction of $V_M$ which was significantly greater than the reduction caused by elevation of $[K^+]_o$ from 4.7 to 11.5 mM in normal Tyrode's solution (Fig. 7). Net cellular $K^+$ loss, which most likely was the cause of this extra- depolarization, occurred without a concomitant increase of $a_{Na}^\infty$. The mechanism of net $K^+$ efflux and the identity of the ions which account for electroneutrality remain to be elucidated (see Kléber, 1984).

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INDEX TERMS: Intracellular sodium • Hypoxia • Acidosis • Hyperkalemia
The combined effects of hypoxia, high K+, and acidosis on the intracellular sodium activity and resting potential in guinea pig papillary muscle.

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