

Active Transport of Potassium by the Giant Neuron of the *Aplysia* Abdominal Ganglion

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ABSTRACT We measured the internal potassium activity, a_{K}^i , and membrane potential, E_m , simultaneously in 111 R2 giant neurons of *Aplysia californica*. a_{K}^i was 165.3 ± 3.4 mM, E_m was -47.8 ± 0.9 mv, and E_{K} calculated using the Nernst equation was -76.9 ± 0.05 mv. Such values were maintained for as long as 6 hr of continuous recording in untreated cells. a_{K}^i fell exponentially after the following treatments: cooling to $0.5^\circ\text{--}4^\circ\text{C}$, ouabain, zero external potassium, 2,4-dinitrophenol, and cyanide. The effects of cooling and zero potassium were reversible. Potassium permeability was calculated from net potassium flux using the constant field equation and ranged from 2.6 to 18.5×10^{-8} cm/sec. We conclude that potassium is actively transported into this neuron against a 30–40 mv electrochemical gradient.

INTRODUCTION

In contrast to extracellular fluid, intracellular fluid usually has a high concentration of potassium and a low concentration of sodium. Such unequal distribution is believed to result from an energy-requiring active transport process located in the cell membrane (Whittam, 1967). This process has been envisioned as a chemically coupled exchange of internal sodium for external potassium (Hodgkin and Keynes, 1955; De Weer, 1970; Katchalsky and Spangler, 1968) with the reservation that the coupling ratio need not be 1:1. However, it has been suggested for *Aplysia* neurons (Carpenter, 1970) and frog skeletal muscle (Conway, 1964) that potassium distributes passively across the cell membrane in response to a membrane potential generated by an electrogenic sodium pump. Direct measurements of potassium activity, using potassium-sensitive liquid ion-exchanger microelectrodes, suggested but did not prove that potassium is actively transported into the giant neuron of the abdominal ganglion of *Aplysia californica* (R2, according to the nomenclature of Frazier, Kandel, Kupferman, Waziri, and Coggeshall, 1967).

Therefore, the purpose of the present experiments was to determine the intracellular potassium activity and whether potassium is actively transported or passively distributed in this neuron. In addition, the transport system was characterized by treating the neuron with various inhibitors of active transport.

We conclude that potassium is transported into the *Aplysia* neuron, R2, thereby establishing a 30–40 mv gradient. The active transport process is inhibited reversibly by cooling to 0.5°–4°C and in zero-potassium artificial seawater solutions. It is also inhibited by ouabain, 2,4-dinitrophenol, and cyanide. A preliminary account of some of the results has been reported (Russell and Brown, 1972 *a*).

METHODS

The preparation and recording methods have already been described (Russell and Brown, 1972 *c*).

The composition of the artificial seawater (ASW) (Hayes and Pelluet, 1947) bathing the ganglion was described in the preceding paper. In the experiments using ASW containing 0 mM potassium, hereinafter referred to as 0-K⁺-ASW, Na⁺ and K⁺ were exchanged on an equimolar basis. All chemicals used were analytical reagent grade.

The fabrication of K⁺-sensitive liquid ion-exchanger microelectrodes was described by Walker (1971). The electrodes were calibrated in a series of KCl solutions varying in activity from 6.05×10^{-1} to 9×10^{-3} M before and after measuring intracellular activity. These activities were determined by tables in the *Handbook of Chemistry and Physics*, by the extended Debye-Hückel equation (Robinson and Stokes, 1959), and by potassium liquid ion-exchanger macroelectrodes. The values were similar with each method. The calibrating solutions were maintained at the experimental temperatures to be used by placing them in the 0.5 ml chambers on top of the constant temperature bath.

The slope of the electrodes at 20°C was 57–58 mv per 10-fold change in potassium activity. Fig. 1 A illustrates the slope and ASW activity for a single electrode using the solutions of known activity at 20°C. The slopes were 56 and 54 mv at 10° and 1°C, respectively. Such temperature-dependent slope changes are in good agreement with the empirical equation describing the response of these electrodes (Walker, 1971). No change or slight improvement in the selectivity of the electrode for K⁺ over Na⁺ ($K_{K, Na}$) was noted after cooling to 1°C. The recording apparatus, precautions taken to prevent significant drift in the voltage output and the correction procedure for drift of less than 3 mv, were the same as described previously for the chloride-sensitive microelectrode (Russell and Brown, 1972 *c*).

Intracellular potassium activity (a_{K}^i) was calculated as follows:

$$a_{K}^i = a_{K}^o \cdot 10^{\frac{E_i - E_o - E_m}{b}}, \quad (1)$$

where b is the slope of the electrode plotted as E vs. $\log_{10} a_K$; $E_o = b \log_{10} (a_{K}^o +$

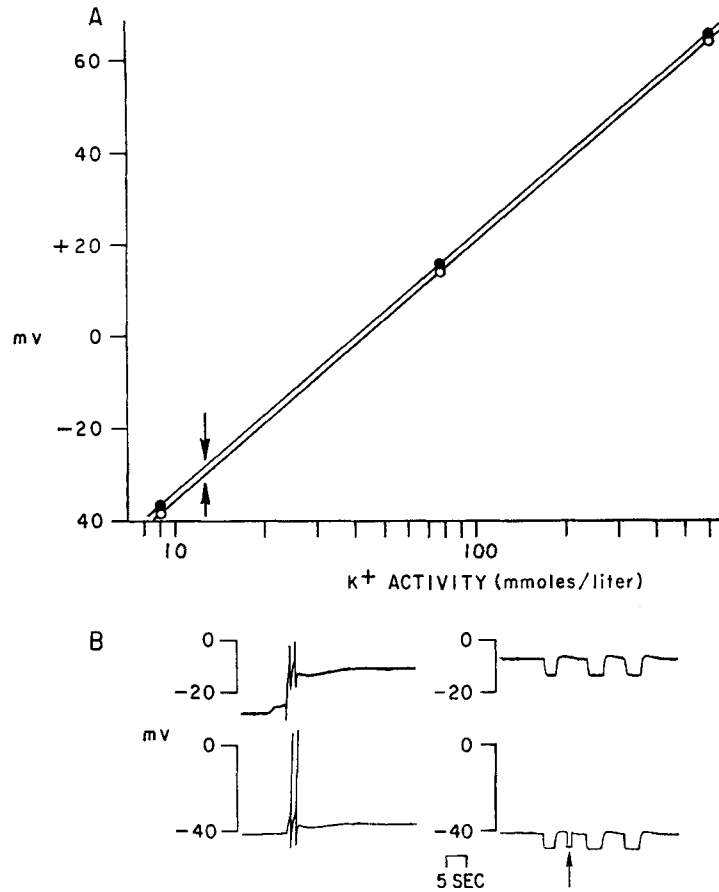


FIGURE 1 A. Plot of potassium-sensitive microelectrode voltage output against potassium activity for a microelectrode before (O) and after (●) it had been used to measure intracellular potassium activity. This microelectrode had an input resistance of 1.4×10^9 ohms, a slope of 57 mv/decade change in potassium activity, and gave an apparent ASW potassium activity of 13 mM (denoted by arrows). This value is higher than the actual potassium activity (7 mM) by the amount of contribution of the sodium ions. During the course of the experiment, a +1.5 mv DC shift occurred.

FIGURE 1 B. Left-hand panel is a penwriter record of the impalement of neuron R2 by the K^+ -sensitive microelectrode. Top trace is the ion electrode output, bottom trace is membrane potential, action potentials are greatly attenuated by the penwriter. The E_o reading before impalement was -30 mv. Right-hand panel is a penwriter record taken 2 min after records in preceding panel. 5 namp of current was passed from a second 3 M KCl-filled micropipette resulting in equal deflection (7 mv) of the E_m record and the E_i record. At this time $E_i = -6$ mv and calculated $a_{K^+}^i = 174$ mM. At the arrow a 7 mv test signal was imposed on the E_m trace.

$K_{K, Na} \cdot a_{Na}^o$), the electrode potential outside the cell; $a_{K}^{\prime} = a_{K}^o + K_{K, Na} \cdot a_{Na}^o$; $E_i = b \log_{10} a_{K}^i + E_m$, the electrode potential inside the cell. The contribution of a_{Na}^i is negligible because the $K_{K, Na}$ is at least 50:1 and a_{Na}^i is less than 25 mM (Russell and Brown, 1972 *b*). Thus, the change in potential observed when a cell is penetrated with a potassium-sensitive microelectrode can be described as follows:

$$E_i - E_o = E_m + b \log_{10} a_{K}^i / a_{K}^{\prime},$$

which can be solved for a_{K}^i to yield equation 1 (Walker, 1971).

Since three voltage measurements are required to calculate a_{K}^i , and each can be read with an accuracy of ± 0.5 mv, the maximum possible error is 1.5 mv. For the range of a_{K}^i generally observed in the present report (100–200 mM), 1 mv is equivalent of 6 mM (see Fig. 1). Thus, a_{K}^i values calculated from single readings of E_i and E_m are accurate to within 9 mM.

Measurement of Reversal Potential of the Action Potential Undershoot

The reversal potential for the hyperpolarizing after potential or undershoot of the action potential was obtained by plotting the difference between the after potential and the preset membrane potential for the different levels of membrane potential. Membrane potential was varied by passing a constant current through a second 3 M KCl-filled micropipette. Action potentials were elicited either by antidromic stimulation or by passing outward current through the cell body membrane.

RESULTS

We measured intracellular potassium activity in 111 giant neurons between December 1969 and December 1971. The average a_{K}^i measured 60–90 min after impalement by the microelectrodes was 165.3 ± 3.4 mM (mean \pm SEM) while a_{K}^o was 7 mM giving an equilibrium potential for potassium (E_K) of -76.9 ± 0.5 mv. This compares with the simultaneously measured membrane resting potential (E_m) of -47.8 ± 0.9 mv. Fig. 2 demonstrates that a_{K}^i remains relatively constant under continuous recording conditions for as long as 6 hr.

Indirect estimates of intracellular potassium content in this neuron have been made from measurements of the equilibrium potential for the negative hyperpolarization after the action potential (E_{us}), the assumption being that E_K equaled E_{us} (Carpenter and Alving, 1968). In nine cells, we measured E_{us} as described in Methods and obtained a value of -60 ± 1.5 mv at 20°C. This compares well with the value of -59 mv obtained by Carpenter and Alving (1968) at 11°C. However, the values for a_{K}^i calculated from this E_K using the Nernst equation range from 75 to 83 mM and differ from our directly measured value by nearly 100 mM. This discrepancy is due to the fact that the slope relating E_{us} to $[K^+]_o$ is 48–52 mv per decade change at 11° and 20°C, respectively (Carpenter and Alving, 1968; Brown, unpublished observations), whereas slopes of 55.5 and 58, respectively,

would be necessary for the membrane to behave like a potassium electrode. It is not surprising that estimates of a_{K}^i by this indirect method are misleading.

It might be argued that K^+ leaking from the tip of the 3 M KCl-filled micropipette artificially increased our directly measured a_{K}^i . Several lines of evidence argue against such leakage having a significant effect. Firstly, a_{K}^i values do not usually show a tendency to increase with time after impalement (Fig. 2 and Table I). We have varied the order of electrode impalement, i.e., KCl first, K^+ -sensitive first, or both simultaneously with no differences in the measured a_{K}^i . Secondly, introduction of a second 3 M KCl-filled micropipette has only very slight or no effect upon a_{K}^i or a_{Cl}^i .

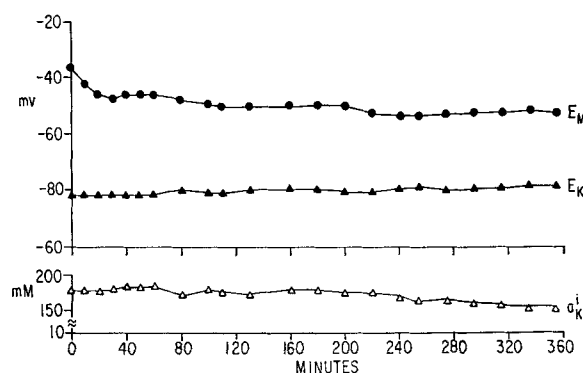


FIGURE 2. Intracellular potassium activity, Δ ; E_{K} , \blacktriangle ; and E_m , \bullet recorded continuously from a single cell for 6 hr (temperature $20 \pm 1^\circ\text{C}$). The symbols used in this figure are used in all subsequent figures. Each data point on this and all succeeding graphs represents the average of three values obtained 1 min apart.

(Russell and Brown, 1972 *c*). Thirdly, a passive leak from the 3 M KCl micropipette would be expected to have even greater relative effects on a_{Cl}^i than a_{K}^i , but we have demonstrated a_{Cl}^i to be relatively steady during 6 hr continuous impalement (Fig. 2, Russell and Brown, 1972 *c*). Finally, we measured a_{K}^i in three neurons whose E_m was measured with either 2 M sodium citrate or 0.6 M Na_2SO_4 -filled micropipettes. The results obtained from these neurons are presented in Table I. As can be seen, a_{K}^i of these neurons was not lower than neurons whose E_m was measured with 3 M KCl-filled micropipettes. Indeed, a_{K}^i increased with time after impalement, perhaps reflecting stimulation of an Na^+ - K^+ exchange pump by a slight leakage of Na^+ into the neuron (Thomas, 1969). In summary, we do not deny the possibility of slight leakage from the 3 M KCl-filled micropipette, but we believe such leakage has minimal effects on our measurements.

Another possibility is that our a_{K}^i values were spuriously high due to an

interfering intracellular cation for which the K^+ -sensitive electrode has low selectivity. Such a possibility can never be entirely discounted, but selectivity constants for the known, common intracellular cations such as sodium, calcium, magnesium, and hydrogen have been determined (Brown, Walker, and Sutton, 1970; Walker, 1971). These constants ranged from 50:1 (potassium over sodium) to 1000:1 (potassium over magnesium), making it unlikely that these ions contribute significantly to our values for a^i_K .

Thus, all the evidence indicates that there is much more free potassium inside this *Aplysia* giant neuron than would be expected if it were passively distributed, suggesting the presence of an active transport system.

TABLE I
EFFECTS OF ELECTROLYTE USED TO FILL MICROPIPETTES ON a^i_K , E_K , AND E_m

Experiments	Experi- ment duration	Initial values			Final values		
		E_m	a^i_K	E_K	E_m	a^i_K	E_K
	hr	mv	mM	mv	mv	mM	mv
3 M KCl-filled micropipettes							
1291	4	-35.7	154.7	-77.9	-44.6	161.7	-79.0
1301	6	-35.5	176.0	-81.2	-52.2	157.5	-78.4
4211	3	-47.5	168.5	-80.2	-47.2	166.5	-79.7
$n = 3$	$\bar{X} \pm SEM$	-39.6 \pm 3.0	166.4 \pm 6.2	-79.8 \pm 1.0	-48.0 \pm 1.5	161.9 \pm 2.6	-79.0 \pm 0.4
2 M Na citrate-filled micropipettes							
461	5	-59.5	199.5	-86.0	-58.3	206.5	-86.6
4261	4	-35.0	161.2	-79.4	-47.5	197.5	-84.0
0.6 M Na_2SO_4-filled micropipette							
3311	4	-53.6	174.0	-80.8	-53.2	187.0	-82.5
$n = 3$	$\bar{X} \pm SEM$	-49.4 \pm 7.4	178.2 \pm 11.3	-82.1 \pm 2.0	-53.0 \pm 3.1	197.0 \pm 5.6	-84.4 \pm 1.2

Effects of Cooling on a^i_K

If maintenance of the transmembrane distribution of potassium is dependent upon cellular metabolism, cooling should cause a^i_K to fall. 10 neurons were cooled to between 0.5° and 4°C after at least 40–80 min of control data were obtained, and $\log a^i_K$ was plotted against time for each neuron (Figs. 3 and 4). After a variable latent period of 10–30 min, a^i_K declined at a rate that could be approximated by an exponential function with a single rate constant (k) during the initial 2–4 hr of cooling. Rate constants were calculated from regression lines (determined in each experiment by the method of least squares) of the plot of $\log a^i_K$ vs. time. Experiments reported here had correlation coefficients for linear regression greater than 0.95; therefore, all points common to a single regression line define the same rate constant.

The average rate constant for these 10 neurons was $3.9 \pm 0.6 \times 10^{-6} \text{ sec}^{-1}$ (mean \pm SEM) (Table II). 3 of the 10 neurons showed a later, quicker decline in a^i_K commencing 2-3 hr after the neuron had been cooled (Fig. 3). This second component had a rate constant of $17.5 \pm 0.7 \times 10^{-6} \text{ sec}^{-1}$. In these three neurons, a^i_K and E_m became relatively constant about 2 hr after the onset of the faster rate constant. At this time, E_K equaled $E_m =$

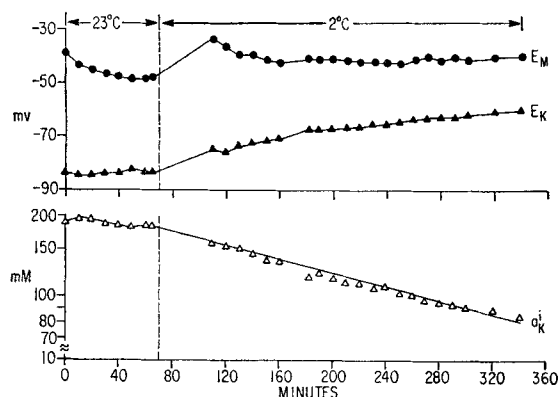


FIGURE 3. Effects of cooling to 2°C on the a^i_K , E_K , and E_m of a single R2 neuron.

TABLE II
EFFECTS OF SEVERAL DIFFERENT TREATMENTS UPON a^i_K , E_K , AND E_m

Treatment	Control			n	70 min after beginning treatment			
	a^i_K	E_K	E_m		a^i_K	E_K	E_m	k efflux
	mM	mv	mv		mM	mv	mv	$\times 10^{-6} \text{ sec}^{-1}$
Cool to 0.5°-1°C	187.9 \pm 7.2	-83.5 \pm 1.1	-47.5 \pm 1.8	10	150.3 \pm 5.8	-73.6 \pm 1.1	-45.4 \pm 1.8	3.9 \pm 0.6
Cool to 10°C	161.8 \pm 4.5	-78.5 \pm 0.5	-49.1 \pm 4.6	4	152.5 \pm 7.6	-77.6 \pm 0.9	-42.4 \pm 5.5	—
Ouabain	165.5 \pm 5.1	-79.4 \pm 0.8	-45.3 \pm 1.5	22	129.6 \pm 4.9	-73.2 \pm 1.0	-36.2 \pm 1.0	6.7 \pm 0.6
O-K-ASW	149.5 \pm 11.0	-76.6 \pm 2.0	-40.2 \pm 2.3	5	116.6 \pm 11.8	-70.6 \pm 1.9	-32.6 \pm 1.1	6.5 \pm 0.7
DNP	153.7 \pm 5.7	-77.8 \pm 0.9	-47.5 \pm 5.0	3	128.5 \pm 11.5	-73.2 \pm 2.3	-38.8 \pm 4.3	4.8 \pm 0.5

All values are mean \pm SEM.

-10 mv. In one such experiment, the neuron was rewarmed to 23°C. a^i_K and E_m began to increase, but E_K was always more negative than E_m during the rewarming period for which data were obtained (Fig. 4).

Four neurons were cooled to 9°-11°C. Although a^i_K decreased in all four neurons (Table II), the decline was smaller and could not be fitted with a smooth exponential function, prohibiting the calculation of a rate constant.

To obtain more information on the nature of the presumed transport process, the effects of ouabain, a well-known inhibitor of the Na-K-activated ATPase system (Glynn, 1964) were examined.

Effects of Ouabain on a_K^i

Ouabain was tested at three concentrations: 2×10^{-5} M, 2×10^{-4} M, and 2×10^{-3} M. There was no significant difference among the three concentrations with regard to rate of fall of a_K^i or amount of membrane depolarization.

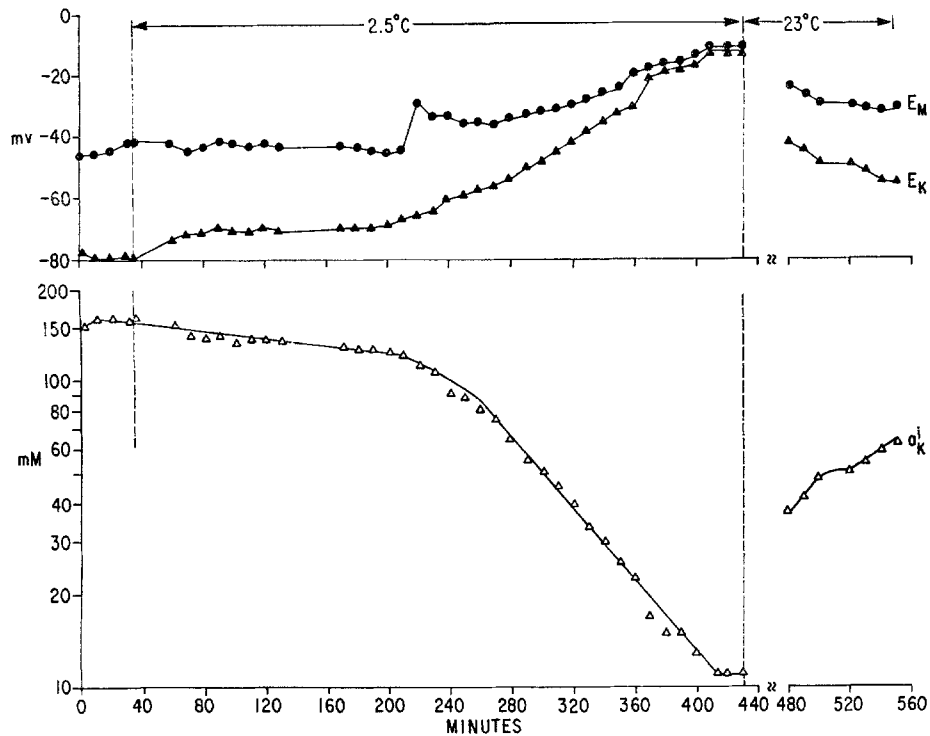


FIGURE 4. Effects of cooling to 2.5°C, then rewarming to 23°C on the a_K^i , E_K , and E_m of a single R2 neuron.

tion in six cells. Therefore, ouabain was used in a concentration of 2×10^{-4} M in all experiments since it approximates that used by workers investigating the electrogenic sodium pump in molluscan neurons (Kerkut and Thomas, 1965; Carpenter and Alving, 1968; Pinsker and Kandel, 1969; Gorman and Marmor, 1970).

22 neurons were treated with ouabain after obtaining 40–90 min of control values. Intracellular potassium activity usually began to decline within 10–20 min of ouabain application, although latent periods of 30–50 min were noted twice (Fig. 5). The average rate constant for the decline of a_K^i

was $6.7 \pm 0.6 \times 10^{-5} \text{ sec}^{-1}$. This value is significantly greater than that obtained after cooling to $0.5^{\circ}\text{--}4^{\circ}\text{C}$ ($P = 0.02$).

Effects of Zero Potassium

Reducing external potassium to zero should completely prevent any uptake of potassium. This is true only if the potassium activity of the fluid in immediate contact with the neuronal membrane is zero. It is doubtful if such an ideal situation can actually be achieved in a neuron with a highly irregular surface closely apposed with glia. To approach this goal, the cell was dissected free of surrounding neurons and the $0\text{-K}^+\text{-ASW}$ solution was flowed at $3\text{--}7 \text{ ml/min}$ past the neuron.

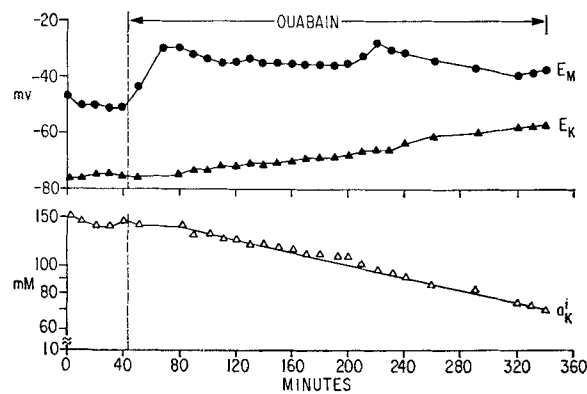


FIGURE 5. Effects of ouabain ($2 \times 10^{-4} \text{ M}$) on the a_{K}^i , E_{K} , and E_m of a single R2 neuron.

Five neurons were treated for from 25 to 100 min with $0\text{-K}^+\text{-ASW}$. After a period of 5–20 min, a_{K}^i began decreasing (Fig. 6). The average rate constant for all five neurons was $6.5 \times 10^{-5} \text{ sec}^{-1}$. This value is significantly different from the value after cooling ($P = 0.02$) but does not differ significantly from that after ouabain ($P > 0.9$).

The effects of $0\text{-K}^+\text{-ASW}$ on E_m and a_{K}^i were fully reversible upon return to control ASW (Fig. 6), and clearly demonstrated an increase in a_{K}^i against its electrochemical gradient.

Effects of Metabolic Inhibitors

Cooling below 4°C , ouabain, and $0\text{-K}^+\text{-ASW}$ all caused a decrease in a_{K}^i and the difference between E_{K} and E_m , which is consistent with the presence of an active transport process for potassium. Cyanide and 2,4-dinitrophenol (DNP) which inhibit oxidative phosphorylation, inhibited active cation

transport in squid axon (Hodgkin and Keynes, 1955). Therefore, it was of interest to examine the effects of these two inhibitors on *Aplysia* neuron R2.

2,4-DINITROPHENOL DNP was applied to two neurons in a concentration of 0.2 mM and to one neuron in a concentration of 1.0 mM. Potassium activity began to fall within 10 min of DNP application, and the decline could be fitted with a simple exponential function. The rate constants were 5.7 and $4.3 \times 10^{-5} \text{ sec}^{-1}$ for 0.2 mM DNP-treated neurons, and $4.4 \times 10^{-5} \text{ sec}^{-1}$ for the 1.0 mM DNP-treated neuron, giving an overall average $k = 4.8 \pm 0.5 \times 10^{-5} \text{ sec}^{-1}$. This does not differ significantly from the rates found after cooling, ouabain treatment, or 0-K⁺-ASW ($P > 0.09$).

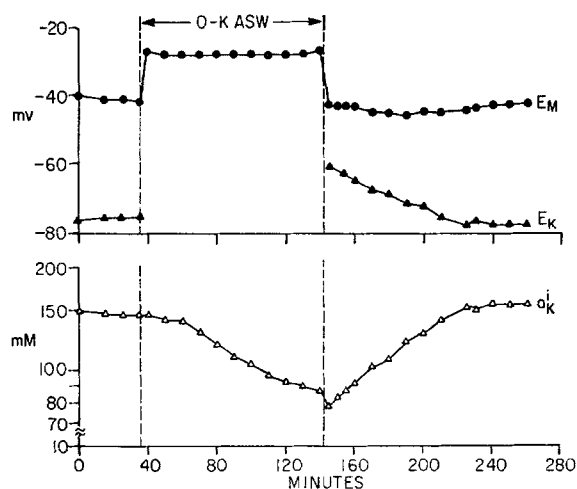


FIGURE 6. Effects of zero K⁺-ASW on the a_K^i and E_m of a single R2 neuron. E_K cannot be calculated when $a_K^o = 0$ (temperature $20 \pm 1^\circ\text{C}$).

There was no difference in the response of E_m to the two concentrations of DNP. E_m declined rapidly for the first 10–30 min after DNP application, and then much more slowly.

POTASSIUM CYANIDE Potassium cyanide was made fresh just before use by substituting KCN for KCl in equimolar quantities.

Three neurons were treated with 5 mM cyanide, a concentration chosen because it exerted a maximal effect on active cation transport in squid axon (Hodgkin and Keynes, 1955). A decline in a_K^i began within 10–30 min of cyanide application and could be fit with a single exponential. The average rate constant was $3.2 \pm 0.3 \times 10^{-5} \text{ sec}^{-1}$.

Since this rate constant was less than that after ouabain, 0-K⁺-ASW,

or DNP ($P = 0.06$), a higher concentration (10 mM) was used in one neuron. In this case, the rate constant for potassium decline was $4.2 \times 10^{-6} \text{ sec}^{-1}$ which is in the range of the values obtained with the other treatments.

Both concentrations resulted in rapid membrane depolarization which averaged 12 mv within 30 min followed by a steady, nonchanging potential for up to 90 min after cyanide application.

DISCUSSION

The data presented in this paper indicate the presence of an active uptake process for potassium in *Aplysia* neuron R2. Thus, control measurements of intracellular potassium activity demonstrate an average difference between the simultaneously measured E_m and E_K of almost 30 mv, E_K being more negative. Further proof of the active uptake of potassium by R2 comes from the results of cooling the neuron to $0.5^\circ\text{--}4^\circ\text{C}$, or treating it with ouabain, $0\text{-K}^+\text{-ASW}$, 2,4-dinitrophenol, or cyanide. All these treatments result in net losses or net efflux of intracellular potassium indicating a dependence of intracellular potassium activity upon cellular metabolism. In addition, it was demonstrated that the effects of cooling to $0.5^\circ\text{--}4^\circ\text{C}$ or exposure to $0\text{-K}^+\text{-ASW}$ were reversible, thereby ruling out irreversible membrane damage as a cause for our observations. It is important to point out that the reversal of the effects of cooling and $0\text{-K}^+\text{-ASW}$ on internal potassium occurred against the electrochemical gradient for this ion.

Determining the exact mechanism of active transport of potassium by this neuron was not the primary object of the present investigation, but the striking similarity of the effects of ouabain and $0\text{-K}^+\text{-ASW}$ strongly implicates the ubiquitous $\text{Na}^+\text{-K}^+\text{-activated ATPase}$ transport system (Whittam, 1967), otherwise known as the sodium pump.

The evidence cited above suggests indirectly that the transport of K^+ inwardly and Na^+ outwardly may be linked, and preliminary studies involving direct measurements of intracellular sodium activity in this neuron (Russell and Brown, 1972 *b*) provides support for such a linkage. This linkage may be rather loose and variable in this neuron. For example, evidence of an electrogenic Na^+ pump in this neuron (Carpenter and Alving, 1968; Carpenter, 1970) which is greatly inhibited by cooling to 10°C (Marchiafava, 1970) has been presented. However, we found that cooling to 10°C had very little effect on a'_K . It is clear from the fact that E_K is 20–30 mv more negative than E_m that whatever the nature and degree of $\text{Na}^+\text{-K}^+$ linkage, the distribution of potassium between intra- and extracellular fluids cannot be considered a passive by-product of an electrogenic pump transporting only Na^+ .

The case for active potassium transport has been definitely proven in squid axon (Hodgkin and Keynes, 1955) and now for an *Aplysia* neuron, and almost certainly it is present in other nervous tissue as well. Thus, the late inhibitory postsynaptic potential in certain other *Aplysia* neurons is thought to be totally potassium dependent and has a reversal potential which is 10–20 mv more negative than the resting potential (Kehoe and Ascher, 1970; Kunze and Brown, 1971). This reversal potential is equivalent to the E_K calculated from the directly measured internal potassium activity in these neurons (Kunze and Brown, 1971).

Potassium Permeability

Assuming that changes in a_K^i reflected net movements of potassium across the neuronal membrane, net efflux of potassium was calculated by the same method as previously described for chloride (Russell and Brown, 1972 *c*). The maximal rate of net potassium efflux ranged from 6 to 8×10^{-12} M/cm² sec. Potassium permeability was estimated using the constant field equation:

$$P_K = M_K \cdot \frac{RT}{FE_m} \cdot \frac{\exp(E_m F/RT) - 1}{a_K^i \cdot \exp(E_m F/RT) - a_K^o}$$

(Hodgkin and Horowicz, 1959), where M_K = net potassium flux, a_K^o = external potassium activity, taken as that of the bulk solution bathing the ganglion, E_m = membrane potential, and R , T , and F have their usual meanings.

Since several treatments caused net K efflux with similar rate constants, it was of interest to compare the permeabilities after each of the treatments assuming complete active transport inhibition by all treatments. P_K was calculated at 10-min intervals throughout each treatment for every cell. Some variability in the P_K value was noted within the values calculated for a single cell. Thus, to obtain a P_K for each individual cell, a mean of all the values calculated for that cell was taken. The average values for all the cells undergoing similar treatment were pooled and an overall average determined for each treatment. Table III gives these overall averages. There was no significant difference among the four treatments ($P = 0.83$), but the 0-K⁺-ASW treatment tended to yield a lower P_K than the other treatments. This fits well with what is known about the effects of changes in external potassium on other excitable membrane systems such as cardiac muscle (Noble, 1966) or skeletal muscle (Hodgkin and Horowicz, 1959). In light of proposed decreases in P_{Na}/P_K caused by cooling certain molluscan neurons (Gorman and Marmor, 1970; Marchiafava, 1970), the lack of effect of cooling on P_K in the present experiments is interesting.

Two cells whose axons were ligated and then treated with ouabain yielded P_K values of $5.9 - 33 \times 10^{-8}$ cm/sec and $3.9 - 21 \times 10^{-8}$ cm/sec which do not appear to differ significantly from values obtained in intact neurons. Thus, it is again demonstrated that the presence of the axon does not influence the permeability calculation (Russell and Brown, 1972 *c*).

The present P_K values may be compared with those of 1.02 and 0.5×10^{-6} cm/sec⁻¹ reported for squid axon by Shanes and Berman (1955) and Hurlbut (1970), respectively, and 1.6×10^{-6} cm/sec reported for frog skeletal muscle by Hodgkin and Horowicz (1959).

TABLE III
CALCULATED POTASSIUM PERMEABILITY RANGES FOR
NEURON R2 AFTER INHIBITION OF ACTIVE
TRANSPORT BY SEVERAL MEANS

	Cooling to 0.5-1°C	Ouabain	0-K ⁺ -ASW	DNP
$P_K \times 10^{-8}$ cm/sec	3.0-17.2	3.3-18.6	2.6-14.3	3.0-17.2

Nature of Intracellular Potassium in Aplysia Neurons

The average concentration of potassium in *Aplysia* neurons has been reported to be 232 mM (Sato, Austin, Yai, and Maruhashi, 1968). Assuming this value and using our average potassium activity of 165 mM, the intracellular activity coefficient for this ion is 0.71 as compared to 0.70 for the fluid outside the cell. This value suggests that potassium is free inside these cells. The result differs from an interpretation of Carpenter, Hovey, and Bak (1971) who found that the internal conductance of *Aplysia* neurons was about 10% of that of seawater. They concluded that the principal internal cation, potassium, must be mainly bound rather than free. However, it has been shown that ionic conductances may be markedly reduced in the presence of nonelectrolytes (Steel, Stokes, and Stokes, 1958; Brown, Walker, Kunze, and Brown, submitted for publication) without any change in ionic activities. Therefore, we do not consider that the low internal conductance of *Aplysia* neurons invalidates in any way our measurements of internal potassium activity.

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