Hemisodium, a Novel Selective Na Ionophore

Effect on Normal Human Erythrocytes

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ABSTRACT Hemisodium is a novel Na ionophore that belongs to the class of compounds called cryptands. These compounds possess an electron-rich cavity for binding of cations and are conformationally organized during synthesis to favor the selective binding of one cation over another. In media containing 145 mM NaCl and 5 mM KCl, hemisodium (10⁻⁵ M) increased erythrocyte Na content from 23 to 345 mmol/kg dry cell solid (dcs) over 4 h and increased water content from 1.8 to 3.5 liter/kg dcs over the same period. K content decreased somewhat over the same time period, but this fall in K content was prevented entirely by incubation in either low Na media (to prevent net Na entry) or in Cl free media. Thus, the decrease in K content in high NaCl media was due to cell swelling, which activated KCl cotransport, and not due to a direct action of hemisodium on K permeability. Hemisodium-mediated Na transport was conductive, because erythrocyte membrane potential (V_m), determined by diS-C₅-5 fluorescence, changed from -9 to +22 mV in high Na media in the presence of hemisodium and DIDS. In cells equilibrated with sulfamate, an anion with low conductive permeability, V_m changed 54 mV per 10-fold change in external Na concentration with the addition of hemisodium. In contrast, a 10-fold change in the external concentration of K, Rb, Cs, or Tl failed to alter V_m in the presence of hemisodium, suggesting a high Na specificity of the ionophore. Na conductance determined from net fluxes increased from 0.04 to 5.2 μS/cm² with 10 μM hemisodium, and with that concentration the ratio of Na to K conductance was 45:1. Among the Na ionophores available so far, hemisodium appears to have the greatest specificity. Hemisodium may be a valuable tool in membrane transport studies.

INTRODUCTION

Ionophores are compounds that facilitate ion transport across cell membranes by forming transportable complexes with ions (carrier mechanism) or by forming pores...
within the membrane (channel mechanism). Ionophores have been widely used in membrane transport research to probe mechanisms of channels and carriers in membranes (Mueller and Rudin, 1967; Szabo, Eisenman, and Ciani, 1969; Cass, Finkelstein, and Krespi, 1970), to alter the cation content of a variety of cell types including erythrocytes (Cass and Dalmark, 1973) and cultured HeLa cells (Ikehara, Yamaguchi, Hosokawa, Yonezu, and Miyamato, 1986), and to alter the membrane potential (Kracke and Dunham, 1987).

While highly specific K ionophores (valinomycin and its depsipeptide analogues) are available, the known Na ionophores available at present (nystatin, gramicidin) are somewhat nonspecific and in particular show poor Na-K discrimination (Cass et al., 1970; Myers and Haydon, 1972; Cass and Dalmark, 1973), which limits their usefulness in many applications. Even monensin, a relatively specific Na ionophore, has a Na:K selectivity of no more than 10:1 (Pressman and Fahim, 1982). A highly specific Na ionophore is not available at present.

Hemisodium, whose structure is depicted in Fig. 1, belongs to a class of compounds called hemispherands. Hemispherands were designed and synthesized specifically as host compounds for cations (Cram, 1986). They possess an electron-rich cavity which provides the binding site(s) for the cation of interest. At least half the binding sites of hemispherands have been conformationally organized during synthesis so as to favor the selective binding of one cation over another (Koenig, Lein, Stuckler, Kaneda, and Cram, 1979; Cram, 1986). In the case of hemisodium (Fig. 1), the binding cavity was constricted with the aim of producing a selective increase in Na permeability (Toner, Daniel, Wood, Feltz, and Luss, 1984). While hemisodium has been reported to increase Na selectivity dramatically in thin-film solvent/polymeric membrane electrodes (Battaglia, Chang, and Daniel, 1980), there are no known reports of the effects of hemisodium in biological tissues. Because of the importance of a selective Na ionophore as a tool in membrane transport research, we investigated the effects of hemisodium using intact human erythrocytes as a model for ion transport. Our results suggest that hemisodium is a highly specific Na ionophore.

Portions of this work were published earlier in abstract form (Kaji and Malik, 1990).
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MATERIALS AND METHODS

Preparation of Cells

Heparinized blood was collected from four normal volunteers and two patients with sickle cell anemia and processed within 60 min of collection. Blood was centrifuged at 600 g for 10 min and the buffy coat was aspirated. The cells were washed three times in a wash solution containing 150 mM N-methyl glucamine (NMG) Cl, 5 mM dextrose, and 5 mM Tris HCl, pH 7.4 at 37°C, and packed to a hematocrit of 75–80%.

Intracellular Na, K, and Water Content

Cell electrolytes were measured by flame photometry of lysates from washed cells as described in previous publications (Kaji, 1989, 1990). Water content of fresh cells was measured by drying 0.1 ml of wet cells to a constant weight in an oven at 100°C for 24 h (Kaji, 1989, 1990). Under conditions of rapid cell swelling, the water content of cells was calculated from their mean corpuscular hemoglobin concentration (MCHC) as described (Kaji, 1986).

Anion Equilibration

Cells were equilibrated in media with 150 mM sulfamate substituting for Cl as described by Dunham, Stewart, and Ellory (1980). Cells were first washed in media with 150 mM sulfamate and then incubated three times at 37°C for 60 min in the same media; cells were washed and resuspended between incubations. Finally, cells were washed three times in the same medium at room temperature. Complete anion equilibration was confirmed by the finding of normal cell water content and undetectable cell Cl content; the latter was measured as described previously (Kaji, 1989).

Membrane Potential (V_m)

Calibration. Membrane potential was calibrated by measuring the change in fluorescence of the carbocyanine dye with 1 μM valinomycin in cells at known potentials (Hoffman and Laris, 1974). V_m was modified by varying K gradients in the presence of valinomycin (1 μM) and DIDS (50 μM). Under these conditions, V_m approaches E_K and was assumed to be equal to (RT/F) ln ([K]/[K_o]), where [K] and [K_o] represent intracellular and extracellular K (millimolar), and F, R, and T have their usual meanings. Cells (3 μl) were added to media (2 ml) containing 150 mM (KCl + NMGCI), 5 mM dextrose, 0.05 mM DIDS, 0.2 μM dis-C3-5, and 5 mM Tris-MOPS, pH 7.4 at 37°C. After reading the fluorescence, valinomycin was added (1 μM final concentration) and the change in fluorescence was recorded 90 s after the addition of the ionophore. The linear relation between the change in fluorescence and V_m in the range of 10–100 mM [K] was used to calibrate the V_m for hemisodium studies.

Measurement of V_m with hemisodium. The method for measuring the fluorescence change with hemisodium was the same as above except that (a) 10^-3 M hemisodium was added instead of valinomycin to initiate the change in V_m, and (b) the media contained 150 mM Cl or sulfamate salts of (Na + NMG). All other conditions including the hematocrit and the dye concentrations were identical to those used for the calibration curve. The change in fluorescence with hemisodium at any given [Na] was then converted to V_m using the calibration curve (see above), which was performed on the same batch of cells immediately before this experiment.
**Transference Number**

The transference number for a cation was calculated as described by Grinstein, Clarke, Dupre, and Rothstein (1982) by using the equation,

\[ T_j = \frac{dV_m}{(RT/F) \ln \left( \frac{C_1}{C_2} \right)} \]

where \( T_j \) is the transference number for the \( j \)th ion, \( dV_m \) is the change in \( V_m \) on varying the concentration of the \( j \)th ion from the initial \( (C_i) \) to the final \( (C_f) \) value, and \( R, T, \) and \( F \) have their usual meanings.

**Calculation of Relative Permeabilities for Cl and Sulfamate**

We calculated the ratio \( P_{\text{sulfamate}}/P_{\text{Cl}} \) by measuring valinomycin-mediated K efflux from erythrocytes equilibrated with Cl or sulfamate (see anion equilibration, above) and suspended at 1% hematocrit in 150 mM NaCl or Na sulfamate. In the presence of 1 mM valinomycin, K efflux is limited only by the permeability of the accompanying anion. Hence, Cl and sulfamate permeability can be approximated from K efflux (Hunter, 1977; Haas, Schmidt, and McManus, 1982; Knauf, Law, and Marchant, 1983). While the calculation of absolute Cl and sulfamate permeability requires constant field assumptions which may or may not be satisfied strictly, the ratio of permeabilities is relatively assumption free.

**Alteration of Cell Electrolytes**

The nystatin method of Cass and Dalmark (1973) was used to prepare cells with equal Na and K concentrations. Cells were incubated at 4% hematocrit in media containing 75 mM NaCl, 75 mM KCl, 35 mM sucrose, 20 mg/liter nystatin, and 2.5 mM HEPES, pH 7.2 at 4°C for 15 min in the dark. The procedure for washing cells and eluting nystatin has been described in detail previously (Kaji, 1986, 1989). The final cell Na and K concentrations were 73.1 ± 0.9 and 77.3 ± 1.3 mmol/liter cell water, respectively, and the water content was 1.77 liter/kg dry cell solid (dcs).

**Na and K Conductance**

Na and K conductances were calculated from the equation of Hodgkin and Huxley (1952),

\[ g_M = \frac{I_M}{(V_m - E_M)} = \frac{J_M F}{(V_m - E_M)} \]

where \( I_M \) is the current of ion M (Na or K), \( J_M \) is the net flux of monovalent cation in moles per square centimeter per second, \( F \) is the Faraday constant, and \( E_M \) is the equilibrium potential for the ion. \( V_m \) was determined from the change in fluorescence of carbocyanine dye as described above, and \( E_M \) was determined from the measured intracellular and extracellular concentrations as \( \frac{(RT/F)}{\ln [M_i]/[M_o]} \). Net Na and K effluxes were measured as described below.

**Net Na and K efflux**. Cells altered with nystatin to contain approximately equal Na and K (see above) were incubated in media with (mM): 10 NaCl, 10 KCl, 130 NMGCl, 5 glucose, 5 Tris-HCl, pH 7.4 at 37°C. The media also contained 0.5 mM ouabain and 0.01 mM bumetanide. Efflux was initiated by adding 10 mM hemisodium. Net Na and K fluxes in millimoles per liter original cells per minute were calculated from the decrease in cell Na and K content over 3 min. For converting Na and K efflux from millimoles per liter original cells per minute to micromoles per square centimeter per second, 1 liter of original cells was assumed to correspond to \( 1.75 \times 10^7 \) cm² (Vestgaard-Bogind, Stampe, and Christophersen, 1987).

**Zero current Na conductance (\( g_{Na}^0 \)).** \( g_{Na}^0 \) was calculated from unidirectional Na fluxes at equilibrium, using the equation of Hodgkin and Keynes (1955). This method has been used to...
calculate ionophore-mediated increase in $g_\text{Na}$ in sheep erythrocytes (Tosteson, Andreoli, Tiffen-berg, and Cook, 1968). Intracellular Na and K were set at 10 and 90 mM so that $E_{\text{Na}} = E_{\text{K}} = E_{\text{Cl}} = V_m$. The resting $V_m$ of these cells, determined from the fluorescence of diS-C3-5, was $-9.5$ mV. Unidirectional ${}^{22}\text{Na}$ influx was measured by incubating erythrocytes in media containing 10 mM NaCl, 90 mM KCl, 50 mM MgCl$_2$, 5 mM glucose, and 5 mM Tris-HCl, pH 7.4 at 37°C with a tracer quantity of ${}^{22}\text{Na}$ and various concentrations of hemisodium for 15 min. Preliminary studies confirmed that the steady-state fluxes were linear up to 20 min with the highest concentrations of hemisodium. Na conductance was calculated as

$$g_{\text{Na}}^0 = \left(\frac{F^2}{RT}\right)J_m$$

(3)

where $g_{\text{Na}}^0$ is the zero current Na conductance in microsiemens per square centimeter, $J_m$ is the unidirectional Na influx in micromoles per centimeter$^{-2}$ per second$^{-1}$, and $F$, $R$, and $T$ have their usual meanings.

**Water Content of LLC-PK1 Cells**

LLC-PK1 cells were purchased from American Type Culture Collection (Rockville, MD) and maintained in Dulbecco’s modified Eagle media (DMEM) with 10% fetal bovine serum and 2 mM L-glutamine at 37°C in a 5% CO$_2$ atmosphere (Amsler and Cook, 1982). Water content was measured by the method of Kletzin, Paiza, Becker, and Potter (1975) from the distribution of the nonmetabolized hexose 3-O-methyl [14C]glucose. Briefly, monolayers of cells grown on plastic Falcon six-well plates were incubated in 2 ml of DMEM containing 1, 2, 5, or 10 mM 3-O-methyl [14C]glucose for 30 min at 37°C. The medium was removed and cells were washed four times with ice-cold phosphate-buffered saline containing 1 mM phloretin, which prevented the efflux of hexose from the cells during washing. The cells were solubilized with 0.2% SDS and cell extracts were counted for 14C radioactivity. Protein content was measured by the fluorescence of tryptophan using method of Avnir and Wallach (1971). Since hexose concentration equalizes in the intracellular and extracellular compartments, the uptake of 3-O-methyl D-glucose gives the intracellular water content, which was expressed as microliters per milligram protein.

**Solutions, Chemicals, and Drugs**

Hemisodium was obtained from Eastman Kodak Co. (Rochester, NY) (catalog No. 185-2912) and dissolved in a 9:1 mixture of ethanol:DMSO to prepare a 10-mM stock solution. The compound is no longer in stock. The manufacturer has indicated verbally that the company will synthesize the compound if commercial demand for the product develops. All other reagents were from Sigma Chemical Co. (St. Louis, MO), Alfa Products (Ward Hill, MA), or J. T. Baker (through VWR Scientific, Piscataway, NJ). ${}^{22}\text{Na}$ was obtained from Amersham Corp. (Arlington Heights, IL).

**Presentation of Data**

Results are presented as means ± standard deviation unless stated otherwise. Because of variation in the absolute rate of K efflux in cells from different donors, the results from different donors have not been pooled. Instead, representative studies are shown in figures. In each case, similar results were obtained in two or more separate studies with cells from different donors. Experimental data points were fitted to equations using nonlinear regression with successive iteration using commercial software packages (Enzfitter; Elsevier-Biosoft, New York, NY, and Sigmaplot; Jandel Scientific, Cortes Madera, CA).
RESULTS

Effect of Hemisodium on Erythrocyte Na, K, and Water Contents

Na content. Hemisodium (10^{-5} M) produced a dramatic increase in intracellular Na content of normal erythrocytes, from 23 to 348 mmol/kg-dcs over a period of 4 h (Fig. 2, closed circles). The hemisodium-induced increase in intracellular Na content was similar in the absence (closed circles) and presence of ouabain (closed squares). The curves for hemisodium and for hemisodium plus ouabain, corrected for zero time values, were well fitted according to the first-order equation Na'c = Na'c' (1 - e^{-kt}) (Eq. 4), where Na'c and Na'c' are the Na contents in millimoles per kilogram per dry cell solid at time t and infinity, respectively, and k (min^{-1}) is the rate constant for influx. The computed initial rates of influx were 3.02 mmol/kg·(dcs·min)^{-1} with hemisodium alone and 3.45 mmol/kg·(dcs·min)^{-1} with hemisodium and ouabain.

In control cells incubated in the absence of hemisodium, intracellular Na content increased only slightly, from 23 to 38 mmol/kg-dcs over 4 h in the absence of ouabain (open circles) and from 24 to 54 mmol/kg-dcs in the presence of ouabain (open squares).

K content. K content of normal erythrocytes decreased from 263 to 155 mmol/kg·dcs over 4 h with the addition of 10 μM hemisodium (Fig. 3, closed circles). The decrease in K content was somewhat greater (from 253 to 123 mmol/kg·dcs) in the presence of hemisodium and ouabain (closed squares). The rates of K efflux with hemisodium alone and hemisodium plus ouabain were 0.42 ± 0.04 and 0.53 ± 0.06 mmol/kg·dcs·min^{-1}, respectively.

Without hemisodium, cell K content decreased minimally, to 255 without ouabain (open circles) and to 242 with ouabain (open squares) over 4 h.

In control cells incubated in the absence of hemisodium, intracellular Na content increased only slightly, from 23 to 38 mmol/kg-dcs over 4 h in the absence of ouabain (open circles) and from 24 to 54 mmol/kg-dcs in the presence of ouabain (open squares).
While the rate of K efflux with hemisodium was small compared with the rate of Na entry, it was nonetheless important to distinguish whether the increase in K transport was consequent to a direct effect of hemisodium on K permeability, or an indirect consequence of cell swelling which activates KCl cotransport (Kaji, 1986; for review see Dunham, 1989). To distinguish between these possibilities, we examined the effect of hemisodium on erythrocyte K content under conditions designed to minimize cell swelling. To achieve a steady cell volume, external Na concentration was kept low at 10 mM (NMGCl replacement). Intracellular Na concentration was 14 mM in this experiment. Under these conditions, despite a large outwardly directed K concentration gradient ([K]_i = 137 mM, [K]_o = 5 mM), cell K content remained virtually unchanged after 4 h in 150 mM Cl media (252 at 4 h vs. 264 mmol/kg·dcs initial; Fig. 4, triangles). In contrast, the decrease in K content was striking in these
cells when they were swollen by incubation in high (145 mM) Na media (Fig. 4, squares). Thus, the effect of hemisodium on cell K observed in Fig. 3 was secondary to activation of KCl cotransport due to cell swelling and not a direct effect of hemisodium on K permeability. The striking decrease in cell K content was also circumvented in Cl free media (145 Na sulfamate, 5 mM K sulfamate), which also prevents activation of KCl cotransport (274 to 263 mmol/kg-dcs at 60 min; not shown). Cell K content measurements became unreliable in this experiment after 90 min because of severe lysis, which was probably secondary to Na gain in the absence of K loss, leading to greater cell swelling.

**Water content.** Erythrocyte water content increased from 1.79 to 3.70 liter/kg-dcs with hemisodium and to 3.59 liter/kg-dcs with hemisodium and ouabain (Fig. 5). The curves for hemisodium alone (closed circles) and for hemisodium plus ouabain (closed squares) were fitted with first-order equations similar to those described for Na (see Legend to Fig. 2). The rates of water influx for hemisodium and hemisodium plus ouabain were 0.005 and 0.0076 liter/kg-dcs·min⁻¹, respectively. For hemisodium plus ouabain, the rate constant was 0.0076 min⁻¹, and the values for \( W_c \) at zero time and equilibrium were 1.83 and 4.4 liter/kg-dcs, respectively.

Without hemisodium, water content increased only slightly over 4 h to 1.96 liter/kg-dcs without and 1.98 liter/kg-dcs with ouabain (Fig. 5, open symbols).

We next examined the correlation between the gain in water content and the net gain in cation content. The gain in water content, which was due to entry of sodium, was attenuated by the simultaneous loss of K. Water content increased in direct proportion to the net gain in (Na + K) content. The concentration of the solution entering the cytoplasm, calculated from the slope of regression line plotting (Na + K) content versus water content, was 167 mmol/liter cell water, which is close to isosmotic (not shown).
**Effect of Hemisodium on Na, K, and Water Content of Sickle Cell Erythrocytes**

In erythrocytes from two subjects with sickle cell anemia, Na content increased from 58 to 310 mmol/kg·dcs in the first subject and from 28 to 310 mmol/kg·dcs in the second subject with sickle cell anemia (Table I). The decrease in K content was much greater in sickle cell (SS) erythrocytes (Table I). This finding is consistent with earlier reports of greater activity of KCl cotransport in swollen sickle erythrocytes (Brugnara, Bunn, and Tosteson, 1986). As in normal cells, this decrease in erythrocyte K content was abolished in NO₃ media (not shown). The water content of SS erythrocytes increased markedly with hemisodium (1.80 to 2.97 liters/kg·dcs over 4 h; Table I), but this rise was less than that observed in normal erythrocytes, consequent to the greater decrease in K content in SS erythrocytes.

### Table I

| Minutes | Subject 1 | Subject 2 |
|---------|-----------|-----------|
|         | Na        | K         | Water     | Na  | K  |
| 0       | 57.9      | 267.4     | 1.80      | 27.9| 232|
| 5       | 61.9      | 256.2     |           |     |    |
| 20      | 108.4     | 246.7     |           |     |    |
| 30      | 131.6     | 229.0     |           |     |    |
| 60      | 178.0     | 209.9     |           |     |    |
| 120     | 247.7     | 164.8     | 2.97      | 310.1| 109|
| 240     | 309.6     | 95.5      |           |     |    |

Erythrocyte Na, K, and water contents of SS erythrocytes with 10⁻⁴ M hemisodium. The media were identical in composition to those described in the legend to Fig. 2. Because of the small quantity of blood obtained from subject 2 with sickle cell anemia, only limited measurements of cation content were possible.

**Concentration Dependence**

In 145 mM NaCl media, an increase in cell Na content, measured in normal (Hb AA) erythrocytes at 3 h, was observed at hemisodium concentrations as low as 0.2 μM (Fig. 6, left). The effect was progressively greater up to 10 μM, the highest concentration used in this study. Because of extensive cell lysis at 3 h, cell Na and water content at higher hemisodium concentrations could not be measured accurately. Water content also increased progressively with a 3-h exposure to hemisodium and high Na media (Fig. 6, right). Water content was 3.2 liter/kg·dcs at 10 μM hemisodium, compared with a value of 1.74 liter/kg·dcs in control cells not exposed to the ionophore. At 5 h, the Na and water contents were 9 and 6% higher than the corresponding values at 3 h (not shown).

**Membrane Potential**

To evaluate whether hemisodium-mediated Na flux is electroneutral or electrogenic, we evaluated the $V_m$ of erythrocyte membranes after exposure to hemisodium. Fig. 7 shows the $V_m$ of normal erythrocytes 2 min after the addition of 10 μM hemisodium plotted as a function of log external Na concentration ([Na]₀). $V_m$ stabilized at a new
value between 90 and 180 s after addition of the ionophore, but some drift in \(V_m\) was noted after 3 min. This drift in \(V_m\) was most likely consequent to an increase in \([Na]_i\) and a resultant change in \(E_{Na}\). However, at 90 s \([Na]_i\) was not appreciably altered even at the highest \([Na]_o\). The \(V_m\) value reported here is the peak value obtained at 90 s.

At a concentration of 10 mM external Na, \(V_m\) was unchanged at -10 mV. This was expected from the measured \([Na]_i\) of 14 mM as \(E_{Na} = E_{Cl} = V_m\). At other external Na concentrations, \(V_m\) increased with increasing \([Na]_o\). The change in \(V_m\) was 24 mV per 10-fold change in \([Na]_o\) in Cl media without DIDS (open circles, dashed line). In the presence of DIDS, which inhibits Cl conductance, the change in potential was 36 mV per 10-fold change in \([Na]_o\) (filled circles, solid line). Thus, the transference number...
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(for calculation, see Materials and Methods) for Na with 10 μM hemisodium was 0.39 and 0.60 without and with DIDS, respectively.

While DIDS is an extremely effective inhibitor of electroneutral anion exchange in the erythrocytes, it inhibits conductive Cl permeability only partially, by 50–85% (Knauf et al., 1983; Bennekou and Stampe, 1988). The lack of Nernstian relationship between $V_m$ and $[Na]_o$ may be due to the substantial Cl permeability that persists in the presence of DIDS. Therefore, we evaluated the relationship between $V_m$ and $[Na]_o$ in cells equilibrated with an anion with an extremely low conductive permeability, sulfamate (Payne, Lytle, and McManus, 1990; see Fig. 8). Using valinomycin-mediated K efflux in Na media as a measure of anion permeability (Hunter, 1977; Haas et al., 1982; Knauf et al., 1983), we found that the conductive permeability for sulfamate was very low with a $P_\text{sulfamate}/P_\text{Cl}$ ratio of 0.06. The baseline $V_m$ in sulfamate-loaded cells in sulfamate media was $-10.3 \text{ mV}$, not different from baseline $V_m$ in Cl media. In sulfamate media with hemisodium, $V_m$ varied by 55 mV per 10-fold change in $[Na]_o$, giving a $T_{Na}$ of 0.94. The small difference between the observed $T_{Na}$ (0.94) and ideal $T_{Na}$ (1.0) may be attributable to permeability to sulfamate, OH (or HCO₃⁻), or both.

**Effect of Hemisodium on Transference Number for Various Cations**

We next investigated the hemisodium-mediated increase in the transference number for various monovalent cations. Cells were incubated in media containing either 10 or 100 mM Li, K, Rb, Cs, or Tl, with NMG replacement. Hemisodium (0.1 mM) was added and the $V_m$ was recorded. Table II shows that there was little or no change in $V_m$ with Li, K, Rb, Cs, or Tl. The transference number was 0.6 with Na and 0.03 or less with all other cations. Thus, hemisodium selectively increased the conductive permeability for Na.
TABLE II
Effect of Hemisodium on the Transference Number of Various Cations

| Cation (mM) | Baseline | With hemisodium (10 µM) |
|------------|----------|------------------------|
| Na         | 0.01     | 0.60                   |
| Li         | 0.02     | 0.03                   |
| K          | 0.01     | 0.01                   |
| Rb         | 0.01     | 0.01                   |
| Cs         | 0.001    | 0.003                  |
| Tl         | 0.001    | 0.002                  |

Membrane potentials were measured in the presence and absence of 10 µM hemisodium. When [Na] was varied, NMGCl replaced Na such that NaCl + NMGCl = 150 mM. When other cations were used, media contained 10 mM NaCl, 10 or 100 mM XCl, and 130 or 40 mM NMGCl. All media contained 5 mM dextrose, 50 µM DIDS, and 5 mM Tris.MOPS, pH 7.4 at 25°C. X represents monovalent cation other than Na. The transference number was calculated as described in Materials and Methods.

Effect of Hemisodium on Na Conductance

To measure Na and K conductance, cells were altered with nystatin to contain 75 mM each of Na and K. These cells were incubated in media containing 10 mM NaCl, 10 mM KCl, and 130 mM NMGCl. Hemisodium was added in various concentrations from 0.1 to 100 µM and the change in $V_m$ was monitored by the change in fluorescence of diS-C₅(5) as described above.

Fig. 9 shows the change in $V_m$ as a function of hemisodium concentration. As Na-loaded cells were suspended in media with low [Na], $V_m$ was −53 mV. With increasing hemisodium concentration, $V_m$ approached $E_{Na}$ and hyperpolarized progressively. Because of these changes in $V_m$, the driving force $V_m - E_{Na}$ decreased with increasing hemisodium concentration. Because $V_m$ was always inside negative (−9 to −37 mV) in this experiment (Fig. 9), the Na and K effluxes measured in parallel experiments (see below) could not be attributed to the voltage-activated, nonspecific cation channel which opens only in cells with inside positive $V_m$ (Halperin, Brugnara, Tosteson, and Tosteson, 1989).
Fig. 10 shows the net Na and K efflux from the same batch of cells at the same hemisodium concentrations. Because hemisodium altered $V_m$, and because the other Na transport pathways (Na-K pump, NaK2Cl cotransport) were inhibited (by adding ouabain and bumetanide), we assumed that net Na and K fluxes in the presence of hemisodium were conductive, and we calculated Na and K currents ($I_{Na}$ and $I_K$ in nanoamperes per square centimeter) from these fluxes as $J_{Na}F$ or $J_KF$, where $J_{Na}$ and $J_K$ are the Na and K effluxes in moles/(square centimeter-second). Despite increasing hyperpolarization, which would tend to retard Na efflux, Na efflux increased with increasing hemisodium concentration (Fig. 10), suggesting that Na conductance must have increased with increasing hemisodium concentration. In contrast, K efflux did not increase appreciably with hemisodium (Fig. 10).

Na and K conductances were calculated from the net Na or K currents (calculated from net fluxes; see Materials and Methods) and the driving force ($V_m - E_M$), where $E_M$ is the equilibrium potential for Na or K. Fig. 11 shows that Na conductance was a linear function of hemisodium concentration on a double logarithmic plot and increased sharply with hemisodium concentration, whereas K conductance was not similarly affected. At 100 μM hemisodium, the ratio of Na to K conductance was 45:1, confirming that hemisodium exhibits a high Na/K discrimination.

Zero Current Na Conductance

Zero current Na conductance ($g_{Na}^0$) was calculated from unidirectional Na fluxes under equilibrium conditions so that $E_{Na} = E_{Cl} = E_K = V_m$ (see Materials and Methods and legend to Fig. 12 for details). Without hemisodium, $g_{Na}^0$ was 0.25 μS/cm². With hemisodium, there was a progressive increase in $g_{Na}^0$. At 100 μM hemisodium, zero current Na conductance reached a value of 6.44 μS/cm². When the log of $g_{Na}^0$ was plotted versus hemisodium concentration (Fig. 12), the plot was linear in the range between $10^{-7}$ and $10^{-4}$ M hemisodium and showed a slope of 0.54 ± 0.05.
Effect of Hemisodium on Renal Tubular Cells

To evaluate whether the effects of hemisodium were confined to erythrocytes or could also be seen in epithelial cells, we examined the effect of 10 μM hemisodium on the water content of LLC-PK1 cells, a cultured renal tubular cell with characteristics of the S2 segment of the proximal tubule. In three separate experiments, hemisodium for 30 min markedly increased the cell water content of LLC-PK1 cells (Table III). While cell Na was not measured because of technical problems, the increase in water content suggests that cell Na content was increased.

DISCUSSION

The lipid layer of cell membranes forms an effective energy barrier to the passage of cations. Ionophores that act as ion carriers or form ion channels reduce this energy
barrier and facilitate the transport of small ions across cell membrane. The study of membrane transport has been greatly facilitated by ionophores (Pressman, 1976). The introduction of hemisodium, a selective Na ionophore, fills a void in the repertoire of tools available to probe transport phenomena.

When hemisodium is added to a suspension of erythrocytes in high Na media (Fig. 2), the resulting Na and K fluxes are mediated by at least three different pathways: (a) the hemisodium-mediated increase in Na permeability, (b) the activation of KCl cotransport, and (c) the activation of a nonspecific cation channel which is irreversibly activated with inside positive potentials (Halperin et al., 1989). Although membrane potentials were not measured pari passu with flux measurements shown in Fig. 2, it appears highly likely from the studies shown in Fig. 7 that the membrane potential of cells in high Na media turned inside positive with the addition of hemisodium. Thus, Figs. 2 and 6 provide a reliable representation of the expected changes in Na content upon addition of hemisodium in high Na media, but should not be used to estimate the direct effect of hemisodium on Na transport.

Ionophore-induced increase in cation permeability may be electrically silent (if the ionophore promotes the exchange of cation for protons or for another cation) or conductive in nature. The change in \( V_m \) with hemisodium upon changing external Na suggests that hemisodium-induced Na transport is conductive.

Na conductance with hemisodium was measured under conditions designed to maintain an inside negative \( V_m \) and thereby avoid the activation of the voltage-gated cation channel (Figs. 9–11). The finding that hemisodium increased Na conductance nearly 40-fold suggests that hemisodium has a direct effect on Na permeability. The ratio of Na to K conductance (with identical Na and K concentrations) was nearly 50-fold, confirming the specificity of the hemisodium effect on the intact cell membrane.

The relationship between ion conductance and the power of ionophore concentration has been used to derive the number of ionophore molecules forming a single transport unit (Cass et al., 1970). In our studies, the slope of the log plot of zero current Na conductance as a function of aqueous hemisodium concentration was 0.5 (Fig. 12). A slope of less than one is difficult to interpret mechanistically in terms of ionophore:ion stoichiometry. One possible explanation for our finding is the saturation of the ionophore in the membrane phase at higher aqueous concentrations. Thus, the slope of Na conductance versus membrane hemisodium concentration may be one (or more), and the slope of less than unity for the aqueous hemisodium

| Water content | Experiment Baseline | Hemisodium (10 µM) |
|---------------|---------------------|---------------------|
|               | µl/mg-protein       |                     |
| 1             | 7.5                 | 11.4                |
| 2             | 7.7                 | 10.5                |
| 3             | 7.2                 | 12.8                |
concentration may be explained by postulating that membrane hemisodium concentration increased less steeply than the aqueous ionophore concentration.

While the precise number of hemisodium molecules forming a single transport unit remains unknown, it is likely to be small. The hemisodium molecule (Fig. 1) appears too small to span the membrane thickness, even with a dimer or a tetramer. Thus, while the possibility that many hemisodium molecules stack together to form a pore cannot be completely excluded, it is more likely that hemisodium acts as a carrier, and combines with Na ion to solubilize it into the hydrocarbon interior of the membrane.

Several lines of evidence suggest that hemisodium increases Na permeability with a greater selectivity compared with other Na ionophores available to date. In thin film solvent polymeric membrane electrodes, hemisodium showed a Na/K selectivity ratio of 167:1 (Toner et al., 1984). In these studies, Na gain was accompanied by little or no K loss despite large K gradients when activation of KCl cotransport was prevented by using sulfamate media. At a concentration of 100 μM hemisodium, the ratio of Na/K conductance was 45:1 (Fig. 11). Finally, in the presence of hemisodium, erythrocyte $V_m$ was not sensitive to large changes in concentrations of external cations other than Na (Table II). Taken together, these findings suggest that hemisodium is highly selective in its action on the Na ion compared with any other ionophore at the present time.

Hemisodium was initially synthesized for technological applications, with the intention of using hemispherand doped membranes as ion-selective electrodes. However, hemisodium appears to have exciting biological and scientific applications over and above any technological application. Thus, hemisodium may be useful in altering intracellular Na concentrations and especially in preparing Na-free cells, a task that is cumbersome with nystatin. In addition, low concentrations of hemisodium in the presence of Cl free media may be used for obtaining cells with the desired degree of cell swelling without alteration of intracellular K concentration. An important use for hemisodium may be to shift $V_m$ away from $E_{Cl}$. In many cell types, Cl is distributed at thermodynamic equilibrium, so that $V_m = E_{Cl}$. A change in the Cl ratio in these cells changes both $V_m$ and the electrochemical Cl potential. Therefore, it becomes nearly impossible to elucidate the mechanism of anion-coupled cation transport unless $V_m$ is shifted away from $E_{Cl}$ (Haas et al., 1982). Shifting $V_m$ away from $E_{Cl}$ by valinomycin is not a good strategy in many cases, because valinomycin-mediated K flux swamps other K fluxes under examination (i.e., Cl-dependent K transport) and renders measurements of anion-dependent K transport impracticable. In these cases, hemisodium may be used to shift $V_m$ away from $E_{Cl}$ and dissect the mechanism of coupled transport. Hemisodium may also be used to probe the dependence of many electrogenic coupled transport processes on membrane potential. The finding that hemisodium was an effective ionophore in cultured renal epithelial cells widens the scope of applications for this compound as a research tool.

In summary, we have described the effects of a novel Na ionophore, hemisodium,
on the cation and water contents and membrane potential of intact normal human erythrocytes. The ionophore appears to exhibit the highest Na selectivity among the Na ionophores available at present. This novel Na ionophore may be a very valuable probe in the study of transport phenomena in general and Na transport in particular.

We thank Dr. Peter M. Cala for some useful discussions and in particular for suggesting the experiments with poorly permeable anions. We thank Dr. T. Kahn and Dr. S. Prabhakar for a careful reading of the manuscript, and Ms. Evelyn Shapiro for secretarial help.

This study was supported by a grant from the Merit Review Grant, Veterans Affairs, Washington, DC.

Original version received 11 July 1991 and accepted version received 25 October 1991.

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