Cationic Selectivity and Competition at the Sodium Entry Site in Frog Skin

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ABSTRACT The cation selectivity of the Na entry mechanism located in the outer membrane of the bullfrog (Rana catesbeiana) skin epithelium was studied. This selectivity was determined by measuring the short-circuit current when all of the external sodium was replaced by another cation and, also, by noting the relative degree of inhibition that the alkali metal cations produced on Na influx. The ability of the Group Ia cations to permeate the apical membrane was determined from the tracer uptake experiments. The results demonstrate that (a) only Li and Na are actively transported through the epithelium; (b) the alkali cations K, Rb, and Cs do not enter the epithelium through the apical border and, therefore, Na and Li are the only alkali cations translocated through this membrane; (c) these impermeable cations are competitive inhibitors of Na entry; (d) the cations NH4 and Tl exhibit more complex behavior but, under well-defined conditions, also inhibit Na entry; and (e) the selectivity of the cation binding site is in the sequence Li ≈ Na > Tl > NH4 ≈ K > Rb > Cs, which corresponds to a high field strength site with tetrahedral symmetry.

INTRODUCTION

The determination of ion selectivity sequences for electrolyte permeation pathways through biological membranes has proved valuable for deducing certain stereochemical characteristics of ligands involved in ion translocation (Hille, 1972 and 1975; Szabo et al., 1973; Moreno and Diamond, 1974; Wright and Diamond, 1977). Knowledge of the chemical constituents of a particular transport entity can provide insight into the molecular process of ion translocation. Recently, much research has been devoted to elucidating the molecular mechanism of the facilitated entry step of sodium across the apical membrane of epithelial tissues, in particular, isolated frog skin. This entry process for sodium displays saturation kinetics and is specifically inhibited by the diuretic compound amiloride (Benos et al., 1976).

A striking property of the Na-entry mechanism in frog skin is its apparent high degree of selectivity, as reflected in its permeability to Na, and its seeming impermeability to K. Lindley and Hoshiko (1964) first addressed the problem of cation selectivity in frog skin by measuring the changes in open circuit (zero current) transepithelial potential as a function of ionic composition in the
outer medium. The underlying assumption was the same one made by Koefoed-Johnsen and Ussing (1958), namely, that changes in ionic composition in one solution elicit changes in the potential of the membrane facing that solution only. These authors concluded that the selectivity sequence was Na > Li > Rb > K > Cs for the outer surface of the bullfrog skin. In the ensuing years, numerous investigators questioned the basic assumption of this study because ionic substitutions of the outer solution lead to complex changes in the potential distribution across the skin under open circuit conditions (Finn, 1974; Reuss and Finn, 1975; Nagel, 1976 and 1977 b). Given these complications, we decided to reinvestigate the cation selectivity of the Na-entry site by a more direct method. The cation selectivity of the Na-entry pathway was assessed in two ways: (a) by comparing the short-circuit currents (Isc), measured when all of the external sodium was replaced by another cation, and (b) by comparing the Isc and net Na fluxes at various [Na]o, using various replacement cations to maintain the ionic strength. We found that of the Group Ia cations, only Li and Na can enter the cells through the apical entry site. Also, K, Rb, Cs, and, under certain conditions, NH4 and Tl, are competitive inhibitors of Na entry, with a selectivity order commensurate with binding to a high field strength site.

MATERIALS AND METHODS

Ventral skins obtained from the bullfrog (Rana catesbeiana) were mounted and equilibrated in Ussing chambers under short-circuit conditions. Transepithelial open-circuit potential and zero-potential (short circuit) current (Isc) were measured with a four-electrode, automatic voltage-clamping device. Dilution potentials were compensated as described by Mandel and Curran (1973). The bullfrogs were obtained from Jacques Well Co., Rayne, La.; only male frogs were used.

The composition of the solution bathing the inner surface of the preparation was 110 mM NaCl, 2.5 mM KCl, 1.0 mM CaCl2, and 5.0 mM Tris, buffered to pH 8.4. The inner surface of the frog skin was always exposed to this solution. The control solution (110 mM Na), which bathed the outside surface of the skin, was identical in all respects, except that it did not contain potassium. Solutions of choline, cesium, rubidium, potassium, ammonium, lithium, and thallium were made up by substituting equimolar concentrations of the chloride salts of these cations for NaCl (in the case of Tl, however, nitrate was the replacement anion in both bathing solutions). Solution changes were made on the outside only. All solutions were continuously bubbled with air and had a pH of 8.4 at room temperature (20°C). In the partial Na replacement experiments, each skin was sequentially exposed to four solutions per test cation, each solution containing a different ratio of [Na]:[Test Cation], (in mM: mM): 110:0; 20:90; 6:104; and 0:110. The Isc observed at every [Na] was then normalized to that observed when [Na]o = 110 mM. The results are presented as the mean value ± one standard error of the mean.

Transepithelial 22Na influxes were measured under conditions in which 90 mM of the external Na was replaced by choline, potassium, cesium, ammonium, or thallium. The influx determinations were performed as described elsewhere (Benos et al., 1976).

The distribution of sodium (22Na), potassium (42K), rubidium (86Rb), and cesium (137Cs) within the skin after exposure from the external solution was measured in comparison to that of [3H]mannitol, a known extracellular marker for frog skin (Biber et al., 1972; Cala et al., 1978). These experiments were performed in the presence of
either 110 mM of the replacement cation or 55 mM Na and 55 mM replacement cation in the external solution. After equilibration in the appropriate external solution, 1 μCi of the cationic tracer and 4 μCi of [3H]mannitol were added to the external medium. After a 15-min exposure, the external solution was removed, the apical surface of the skin was briefly (<5 s) flooded with tracer-free medium, the chamber was rapidly dismantled, and the skin was removed. The exposed area of the skin was quickly excised with a metal punch, blotted, and placed directly in a scintillation vial. The piece of tissue was then dissolved in 1 M NaOH (1 ml) for 24-48 h, neutralized with HCl, and counted after the addition of 10 ml of scintillation fluid. Before chamber dismantling, the samples were removed from both bathing media for counting. The distribution spaces for each of the tracers were calculated according to the method described by Cala et al. (1978). All isotopes were purchased from New England Nuclear, Boston, Mass.

Results

Cationic Selectivity for Translocation

The cationic selectivity of the skin was evaluated by transepithelial $I_{sc}$ and Na flux measurements. Due to the complex morphology of the tissue, it was essential initially to establish that all ionic selectivity measurements pertained to properties of the same transport step. This necessity is illustrated by the results from experiments in which all external sodium was replaced by a test cation (Table I). The $I_{sc}$'s measured under these conditions were normalized to that observed during previous equilibration in external 110 mM sodium. In skins obtained from 28 animals, the absolute value of $I_{sc}$ averaged 46.0 ± 3.3 μA/cm². As can be seen from Table I, only external lithium is actively transported across this epithelium at a rate comparable to Na, as others have found (Zerahn, 1955; Candia and Chiarandini, 1973). The other alkali metal cations abolish $I_{sc}$. The small remaining $I_{sc}$ is amiloride insensitive and not different from what it is in the presence of external choline or even in distilled water.

Which step or barrier in the transepithelial cationic active transport system does not permit the transport of these alkali metal cations? Active transepithelial Na transport in frog skin may be understood as a process that involves two steps: passive Na entry through the apical border into epithelial cells followed by active extrusion through the basolateral side (Koefoed-Johnsen and Ussing, 1958). Therefore, the question is, can these alkali metal cations not be transported because they are unable to permeate the apical border or because they inhibit the Na pump once they enter the epithelial cells?

The second series of experiments measured the distribution space of each of the alkali metal cations (except lithium) when it was present in the external solution. The spaces were determined under conditions of either total cationic replacement or partial replacement of 55 mM NaCl by the appropriate alkali salt. Simultaneously, [3H]mannitol spaces were determined as a measure of extracellular space (Biber et al., 1972; Cala et al., 1978). The results, shown in Table II, demonstrate that Cs, Rb, and K have distribution spaces not significantly different from the external extracellular space; these spaces do not change when active Na transport occurs, as shown in the partial replace-
ment experiments. In contrast, Na has a much larger distribution space, as expected of a substance that penetrates the cellular compartment. These results demonstrate that the $I_{sc}$ is inhibited in the presence of total external replacement by Cs, Rb, and K because these cations cannot permeate the apical border of bullfrog skin.

**TABLE I**

**THE EFFECT OF TOTAL REPLACEMENT OF EXTERNAL SODIUM WITH VARIOUS CATIONS ON $I_{sc}$ OF ISOLATED BULLFROG SKIN**

<table>
<thead>
<tr>
<th>External condition</th>
<th>$n$</th>
<th>Normalized $I_{sc}$ (±SEM) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Lithium</td>
<td>28</td>
<td>113±11</td>
</tr>
<tr>
<td>Potassium</td>
<td>28</td>
<td>3.7±0.5</td>
</tr>
<tr>
<td>Rubidium</td>
<td>28</td>
<td>3.3±0.4</td>
</tr>
<tr>
<td>Cesium</td>
<td>28</td>
<td>3.8±0.5</td>
</tr>
<tr>
<td>Choline</td>
<td>28</td>
<td>3.1±0.4</td>
</tr>
<tr>
<td>Distilled H$_2$O</td>
<td>16</td>
<td>3.2±0.6</td>
</tr>
<tr>
<td>Ammonium*</td>
<td>14</td>
<td>3.1±0.2</td>
</tr>
<tr>
<td>Ammonium‡</td>
<td>6</td>
<td>27±3</td>
</tr>
<tr>
<td>Thallium</td>
<td>8</td>
<td>72±17</td>
</tr>
</tbody>
</table>

Measurements were made ~5 min after solution change.

* Population A.

‡ Population B.

**TABLE II**

**DISTRIBUTION SPACES OF ALKALI METAL CATIONS AND [3H]MANNITOL WHEN APPLIED TO THE EXTERNAL SURFACE OF THE BULLFROG SKIN FOR 15 MIN**

<table>
<thead>
<tr>
<th>External solution</th>
<th>Cationic isotope</th>
<th>Cationic space $\mu l/cm^2$</th>
<th>Mannitol space $\mu l/cm^2$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>110 mM CsCl</td>
<td>$^{137}$Cs</td>
<td>0.33±0.05</td>
<td>0.34±0.09</td>
<td>&gt;0.9</td>
</tr>
<tr>
<td>55 mM CsCl +</td>
<td>$^{137}$Cs</td>
<td>0.38±0.09</td>
<td>0.25±0.02</td>
<td>&gt;0.2</td>
</tr>
<tr>
<td>55 mM NaCl</td>
<td>$^{86}$Rb</td>
<td>0.29±0.05</td>
<td>0.28±0.04</td>
<td>&gt;0.8</td>
</tr>
<tr>
<td>55 mM NaCl</td>
<td>$^{86}$Rb</td>
<td>0.24±0.05</td>
<td>0.27±0.04</td>
<td>&gt;0.6</td>
</tr>
<tr>
<td>110 mM RbCl</td>
<td>$^{42}$K</td>
<td>0.23±0.10</td>
<td>0.28±0.13</td>
<td>&gt;0.8</td>
</tr>
<tr>
<td>55 mM RbCl +</td>
<td>$^{42}$K</td>
<td>0.25±0.08</td>
<td>0.17±0.05</td>
<td>&gt;0.3</td>
</tr>
<tr>
<td>55 mM NaCl</td>
<td>$^{22}$Na</td>
<td>1.18±0.24</td>
<td>0.42±0.07</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

Each set of experiments was performed in eight skins.

In the study of active transepithelial Na transport in frog skin, several investigators have presented evidence that the entry step into the epithelial cells is rate-limiting (Biber, 1971; Mandel and Curran, 1973; Helman and Fisher, 1977; Mandel, 1978). Therefore, the $I_{sc}$ reflects the Na transport properties of that barrier, and alterations of these transport properties will be
reflected in changes in the $I_{sc}$. The permeation of Li through the entry site was studied by Morel and Leblanc (1975), who found the rate to be similar to that for Na. Therefore, we can write the selectivity order of the Group Ia cations for translocation through the apical pathway as Li ≈ Na >> K, Rb, and Cs. Because our techniques can differentiate transport at the 1% level (Table I), Na and Li must be at least 100 times more permeant than K, Rb, and Cs.

**Cationic Selectivity for Inhibition of Na Entry**

Inasmuch as only Na and Li can be transported by the apical entry mechanism, measurements were made to assess the ability of other monovalent cations to inhibit this translocation process. This method compared the currents observed at 20 and 6 mM $[Na]_o$ using various test cations as replacement ions. Initial experiments were performed to establish that the $I_{sc}$ represented active Na transport under these experimental conditions. Transepithelial $^{22}$Na influxes were measured under short circuit conditions in the presence of 20 mM external Na, using choline, K, and Cs as replacement cations. These fluxes were measured on the same frogs in the sequence indicated above. As shown in Table III, the Na influxes are not significantly different from the $I_{sc}$, demonstrating that the $I_{sc}$ measures active Na transport under all these conditions. The magnitude of the $I_{sc}$ in the presence of K and Cs as compared with that in choline should not be interpreted quantitatively because the $I_{sc}$ decays as a function of time in prolonged flux experiments of this sort; the relevant parameter is the comparison between the simultaneously measured fluxes and currents. These measurements were not performed in the presence of Rb. We assume that the same considerations apply to Rb as a replacement cation.

Experiments were next performed to quantitatively evaluate the effects of these replacement cations on $I_{sc}$ in the presence of constant external Na concentrations of 20 and 6 mM. The experiments, summarized in Table IV, were initiated with 110 mM Na in the external solution to serve as the reference $I_{sc}$. The $I_{sc}$ observed at 20 mM Na (66.1 ± 1.0%), with choline substitution for sodium, represent the control values of Na current to which the currents observed with the other cations are compared. This is predicted upon the observation that the $I_{sc}$ measured at varying $[Na]_o$ is the same when determined either at constant ionic strength (with choline) or at varying ionic strength (Mandel and Curran, 1973). We have verified this finding for *R. catesbeiana* skin (Fig. 1). From Table IV, it may be observed that the other alkali metal ions inhibit the $I_{sc}$. When the percent inhibition of $I_{sc}$ is calculated with respect to choline, a sequence of inhibitory action may be determined, which shows that Cs inhibits the least and K inhibits the most.

Because it has been shown that external K is a competitive inhibitor of Na entry (Rotunno et al., 1970; Mandel and Curran, 1973; Benos et al., 1979), we assumed that K competes with Na for binding at a common site. The same assumption may be made with respect to Rb and Cs, since these cations also inhibit Na entry without themselves entering into the cytoplasm from the external solution. Competitive inhibition may be treated quantitatively with
the use of Michaelis-Menten kinetics, the resulting equation being (Segel, 1975)

\[ I_{sc} = \frac{I_{\max} [\text{Na}]_o}{K_i \left( 1 + \frac{[I]_o}{K_i} \right) + [\text{Na}]_o} \]  

(1)

**TABLE III**

TRANSEPITHELIAL $^{22}$Na INFLUXES ACROSS ISOLATED BULLFROG SKIN IN THE PRESENCE OF VARIOUS EXTERNAL REPLACEMENT CATIONS

<table>
<thead>
<tr>
<th>Replacement cation (90 mM) n</th>
<th>$\bar{I}_{\text{Na}}$ (±SEM)</th>
<th>$I_{sc}$ (±SEM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choline</td>
<td>8</td>
<td>0.94±0.14</td>
</tr>
<tr>
<td>Potassium</td>
<td>8</td>
<td>0.40±0.05</td>
</tr>
<tr>
<td>Cesium</td>
<td>8</td>
<td>0.41±0.07</td>
</tr>
<tr>
<td>Ammonium*</td>
<td>4</td>
<td>0.04±0.002</td>
</tr>
<tr>
<td>Ammonium†</td>
<td>4</td>
<td>0.07±0.01</td>
</tr>
<tr>
<td>Thallium</td>
<td>8</td>
<td>0.15±0.01</td>
</tr>
</tbody>
</table>

In all of these experiments the external bathing solution contained 20 mM Na.
* Population A. See text for details.
† Population B. See text for details.

**TABLE IV**

THE EFFECT OF EXTERNAL CATION SUBSTITUTION ON $I_{sc}$ OF ISOLATED BULLFROG SKIN

<table>
<thead>
<tr>
<th>Replacement cation n</th>
<th>[Na]_o</th>
<th>$\bar{I}_{\text{Na}}$ (±SEM)</th>
<th>$I_{sc}$ (±SEM)</th>
<th>$K_i$ or $K_i$ (±SEM)</th>
<th>$\Delta G_i$ kcal/mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choline</td>
<td>8</td>
<td>66.1±1.1</td>
<td>0</td>
<td>10±1</td>
<td>-2.6*</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>31.4±1.0</td>
<td>0</td>
<td>13±1</td>
<td>-2.0</td>
</tr>
<tr>
<td>Cesium</td>
<td>8</td>
<td>53.1±1.9</td>
<td>20±3</td>
<td>168±45</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>22.4±1.4</td>
<td>29±6</td>
<td>131±27</td>
<td>-1.6</td>
</tr>
<tr>
<td>Rubidium</td>
<td>8</td>
<td>44.4±1.4</td>
<td>33±2</td>
<td>76±9</td>
<td>-1.5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>16.0±0.9</td>
<td>49±3</td>
<td>61±6</td>
<td>-1.6</td>
</tr>
<tr>
<td>Potassium</td>
<td>8</td>
<td>34.6±1.2</td>
<td>48±2</td>
<td>39±3</td>
<td>-1.9</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>11.6±0.8</td>
<td>63±3</td>
<td>36±3</td>
<td>-2.0</td>
</tr>
<tr>
<td>Ammonium‡</td>
<td>4</td>
<td>32.6±1.1</td>
<td>52±2</td>
<td>35±3</td>
<td>-1.9</td>
</tr>
<tr>
<td>Thallium</td>
<td>8</td>
<td>25.8±2.2</td>
<td>61±3</td>
<td>22±4</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

Measurements were made 5 min after each solution change was completed.
* This is the $\Delta G_i$ for Na, not choline.
‡ Population A. See text for details.

where $I_{\text{max}}$ is the maximal $I_{sc}$ observed at high [Na]_o, $K_i$ is the [Na]_o at which $I_{sc} = 0.5 I_{\text{max}}$ in the absence of an inhibitor, [I]_o is the external concentration of the inhibitor, and $K_i$ is the concentration of inhibitor that decreases $I_{sc}$ to one-half of its original, uninhibited, value. In Table IV, values for $K_i$ calculated for 20 and 6 mM Na in the presence of choline (absence of inhibitors) are 10
Utilizing the average of these two values ($K_t = 11.5 \text{ mM}$) in Eq. 1, we can calculate values of $K_i$ for each of the other replacement cations at both external Na concentrations. If the replacement cations are indeed competitive with sodium, the value of $K_i$ should be independent of the external Na concentration, as is the case within experimental error (Table IV).

Since the translocation of Na is rate determining, $K_i$ and $K_t$ represent equilibrium dissociation constants for the Na entry site (Mandel, 1978). The Gibbs free energy of binding for each cation may be calculated from

$$\Delta G_j^o = RT \ln (K_j),$$  \hspace{1cm} (2)

where $R$ is the gas constant, $T$ the absolute temperature, and $K_j$ is the equilibrium dissociation constant for ion $j$. The $\Delta G_j^o$ values calculated from Eq. 2 provide a relative selectivity sequence on the basis of binding free energy. Thus, the binding sequence determined from Table IV for the Group Ia cations is Na $>$ K $>$ Rb $>$ Cs. The other alkali metal ion, lithium, is not amenable to this treatment because this ion can itself be transported.

We also attempted to determine the position of ammonium (NH$_4$) and thallium (Tl) in the selectivity sequence to derive additional information concerning ligand type and symmetry within the apical entry site. Experiments similar to those performed with the alkali metal ions were performed with NH$_4$ and Tl with mixed results, as is shown below. In 14 of the 20 skins in which all of the external Na was replaced with NH$_4$ (Table I), the resultant current was identical to that observed when the impermeant cations were present (3.1%), suggesting that NH$_4$ was not transported through this popu-
lation of skins (denoted population A). The normalized \(I_{sc}\) of the six other skins averaged 27% (range, 32.1-18.6%) under identical conditions, indicating that \(\text{NH}_4\) was transported through this population of skins (denoted population B). The presence of two populations of frog skin was again evident as the unidirectional \(^{22}\text{Na}\) influx (\(f_{\text{Na}}\)) was measured when 90 mM external Na was replaced with \(\text{NH}_4\) (Table III). In four of eight skins, \(f_{\text{Na}}\) (3.1 ± 0.2 \(\mu\text{A/cm}^2\)) equaled \(I_{sc}\) (3.4 ± 0.4 \(\mu\text{A/cm}^2\)), and both \(f_{\text{Na}}\) and \(I_{sc}\) were reduced to zero with \(10^{-4}\text{ M}\) amiloride, demonstrating that all the \(I_{sc}\) was due to Na transport. The behavior of these skins may be equated to that of population A, since no \(\text{NH}_4\) was transported. In these skins, the presence of \(\text{NH}_4\) inhibited the \(I_{sc}\) to a normalized value of 32.6% (Table II). In the other four experiments with 20 mM Na and 90 mM \(\text{NH}_4\) in the external solution, \(I_{sc}\) exceeded \(f_{\text{Na}}\) by 5.1 ± 0.5 \(\mu\text{A/cm}^2\), indicating that 42% of the current was carried by other ions, most likely \(\text{NH}_4\). This behavior is similar to that of population B. It is noteworthy that the excess \(I_{sc}\) over \(f_{\text{Na}}\) was not amiloride sensitive, whereas \(f_{\text{Na}}\) itself was totally abolished by external amiloride. This result suggests that, whichever ions are transported under these conditions, this transport (population B) is amiloride insensitive and, thus, likely to occur through a pathway separate from the normal Na-entry pathway. Conversely, the results obtained with population A, demonstrating inhibition of \(I_{sc}\), with no transport of \(\text{NH}_4\), fulfill the requirements for interpretation on the basis of inhibitory ability. Using this population, we fit \(\text{NH}_4\) into the sequence at the same level as K, i.e., \(\text{Na} > \text{NH}_4 \approx \text{K} > \text{Rb} > \text{Cs}\).

The results obtained with Tl were unusual because the \(I_{sc}\) was 72.5% of the control value (Table I) when Tl completely replaced Na, whereas at 90 mM Tl (20 mM Na), Tl acted as an inhibitor of Na entry (Table II). Experiments measuring \(^{22}\text{Na}\) influx revealed that replacement of 90 mM Na with Tl in the external solution produced a long-term (90-min) transient in the \(I_{sc}\), initially inhibiting the current (these are the values reported in Table II) and, thereafter, steadily increasing it to 166.7% of the initial \(I_{sc}\). \(f_{\text{Na}}\) could not be measured during the initial inhibition, but, after 30-60 min of exposure to 90 mM Tl-20 mM Na, \(I_{sc}\) exceeded \(f_{\text{Na}}\) by a factor of 2.6 (32.6 ± 3.3 \(\mu\text{A/cm}^2\) and 12.7 ± 1.3 \(\mu\text{A/cm}^2\); \(n = 8\), respectively, Table III). Under these conditions, even \(f_{\text{Na}}\) became amiloride insensitive. The unusual behavior of Tl in this tissue is not surprising in view of the multiple effects it has in other preparations (see Discussion). Despite these complex effects of Tl, it may still be possible to assign its location in the selectivity sequence for the apical entry step. This may be accomplished by assuming that the initial decrease in \(I_{sc}\) (Table II) is due to competitive inhibition of Na entry. This assumption was made because the initially inhibited current is amiloride sensitive. Thus, under these conditions, the \(I_{sc}\) provides an upper bound for Na current. Using this criterion, we obtain a selectivity sequence for competition with Na entry: \(\text{Na} > \text{Tl} > \text{NH}_4 \approx \text{K} > \text{Rb} > \text{Cs}\).

**DISCUSSION**

The ability to discriminate among monovalent cations has been elegantly described by Eisenman (1962) in terms of the interplay between dehydration
energies and electrostatic interactions with the selectivity site. An important prerequisite for the application of this theory is that the selectivity properties that are actually measured pertain to a single site. Much of the present effort was devoted to ascertaining that the selectivity for transepithelial active Na transport resides at a single site within the apical border of the bullfrog skin. This analysis is predicated on three considerations: (a) only Na and Li permeate through the apical border; (b) the current measured in the presence of replacement cations remains a Na current; and (c) these cations are competitive inhibitors of Na transport.

In terms of the first consideration, the classical experiment of Koefoed-Johnsen and Ussing (1958) suggested that the apical border was permeable to Na but impermeable to K in *Rana temporaria*. Recent results from Hirschmann and Nagel (1978) and Zeiske and Van Driessche (1978) indicate that a small permeability to K is present in these species of frog in the absence of external Na; this K permeability is, however, not amiloride sensitive, indicating that it occurs through another pathway. No evidence for such a pathway was found in bullfrog. Our results (Table II) demonstrate that the distribution of K, Rb, and Cs is extracellular when these ions are present in the external solution. The total cationic replacement experiments (Table I) show that the $I_{sc}$ is inhibited in external distilled H$_2$O and choline to the same extent that it is in K, Rb, or Cs. The small remaining current was not amiloride sensitive and, thus, was unlikely to have originated from residual Na transport. This current was probably not due to net ionic movements through the paracellular shunt pathway either, even though the skin was bathed in asymmetrical solutions. This possibility can be excluded because there is a net inward current when distilled H$_2$O is on the outside of the skin, and there is no difference in $I_{sc}$ when the outside is bathed in 110 mM choline, Rb, K, or Cs, molecules of widely differing free-solution mobility and radii. The origin of this remaining $I_{sc}$ is unknown. One possible explanation is that it is due to Cl leaving the epithelial cells through the apical border and residual cellular Na being transported through the basolateral side, since this current is abolished by serosal ouabain (results not shown).

The second consideration is clearly satisfied by the results shown in Table III, i.e., the measured Na influxes are not significantly different from the $I_{sc}$'s with any of the cationic replacements. The Na influxes do contain a component that transverses the paracellular pathway (Mandel and Curran, 1972); however, this component is small and probably hidden within the standard errors.

Finally, on the basis of the formalism of Michaelis-Menten kinetics, the other alkali metal ions have been shown to compete with Na for binding at its entry site (Table IV). Various laboratories have demonstrated that Na entry saturates as a function of external Na concentration (Kirschner, 1955; Cereijido et al., 1964; Rotunno et al., 1970; Biber and Curran, 1970; Moreno et al., 1973; Erlij and Smith, 1973; Rick et al., 1975; Mandel, 1978) in a manner describable by Michaelis-Menten kinetics. The application of this kinetic description and its justification for use on Na transport in frog skin have been discussed at length in several publications from our laboratory (Benos et al., 1976 and 1979; Mandel, 1978).
Two major types of molecular interpretations have been advanced to explain the observed saturation behavior of sodium entry on frog skin. In the first of these, saturation occurs via a direct interaction of Na and its entry site, whether this site be a carrier (Biber and Sanders, 1973) or a pore (Heckmann et al., 1972). The second interpretation is that the saturation behavior of Na entry occurs by the self-inhibition of Na transport at a modifier site (Lindemann and Voute, 1976; Fuchs et al., 1977). The latter authors have suggested that saturation was not a property of the individual Na entry units themselves but, rather, a result of Na interacting with another site in such a way as to close the entry pathways.

Our experiments cannot differentiate between these two molecular interpretations. However, the kinetic interaction between Na and amiloride has been shown to be different in *Rana temporaria* and *Rana esculenta* (Lindemann and Voute, 1976; Fuchs et al., 1977) as compared with *Rana pipiens* and *R. catesbeiana* (Benos et al., 1979). In *R. temporaria* and *R. esculenta*, Na and amiloride are competitive. Because of this property, Lindemann and Voute (1976) have proposed that the modifier site is also the locus of amiloride's inhibitory action. In our epithelial preparations, amiloride and Na interact noncompetitively, suggesting that they act at separate sites (Benos et al., 1979). This conclusion has been further substantiated in recent studies using site-specific reagents (Benos et al., 1980). Although it is possible that Na acts at a modifier site distinct from the amiloride modifier site, the simplest explanation for these data is that amiloride acts at a modifier site and Na interacts directly with the Na translocation site. Thus, in *R. pipiens* and *R. catesbeiana*, saturation could occur by a direct interaction of Na with the entry sites. The observed competitive inhibition of Na entry by other monovalent cations can thus be interpreted as resulting from the direct interaction of these cations at the Na-translocation site.

The concept of inhibition may be easily understood in terms of the binding energy of the site for the other cations. The selectivity of inhibition is identical to the binding selectivity, that is, the tighter the binding, the more effective the inhibition is. Binding of a competing cation prevents the binding of sodium to its site. These effects of the competing cations manifest themselves in an increased effective $K'_i = K_t (1 + [I]/K_i)$, which cause a decrease in the average binding energy for sodium.

The observed selectivity for the Group Ia cations to the Na binding site (Na > K > Rb > Cs) is that of either sequence X or XI of Eisenman (1962), depending on the position of Li. As shown in Table I, Li is itself transported through the apical border. However, Leblanc (1972) and Nagel (1977 a) found that its presence in the external solution causes Li accumulation in the epithelial cytoplasm that is often accompanied by the presence of large transients in the $I_e$ and decreases in intracellular potential (Nagel, 1977 a). Thus, although an inhibitory $K_i$ has been calculated for Li on Na entry (Biber and Curran, 1970), its interpretation has been questioned by Nagel (1977 a). It may be argued that Li binds to the entry site with comparable energy to that of Na, since their rates of transport into the cell are similar (Morel and
On this basis, we tentatively assign the following place to Li on the selectivity sequence for the binding site: Li ≥ Na > K > Rb > Cs, which falls between sequences X and XI. Either sequence describes a high field strength site which presumably causes partial or total dehydration of the cations. It should be noted that this selectivity sequence is inversely related to ionic radius, and, therefore, the selectivity may also be the result of steric hindrance rather than electrostatic interactions.

Somewhat more information regarding the molecular architecture of this site may be obtained from the behavior of NH₄ and Tl. To investigate whether the selectivity of this site strictly follows the inverse of the ionic radius, it is informative to plot the binding energy vs. ionic radius for all the replacement cations, as done by Moreno and Diamond (1974). As shown in Fig. 2, the binding energy for the alkali metal ions does vary inversely with the ionic radius; however, both NH₄ and Tl possess larger binding energies than would be expected from their ionic radii. For ammonium, this type of behavior is usually interpreted as indicating the presence of tetrahedral symmetry at the site (Eisenman and Krasne, 1973; Moreno and Diamond, 1974). The positive charge in NH₄ is distributed over all five atoms rather than being concentrated on the central nitrogen and, hence, its ability to hydrogen-bond with appropriately placed ligands is enhanced. Since NH₄ has a tetrahedral configuration, a similar array at the site would cause tighter binding. For Tl, additional energy terms are contributed by its electronic polarizability, partial electron transfer, and promotion of electrons to higher energy orbitals (Moreno and Diamond, 1974). Thus, its interaction energies with a variety of binding sites are larger than would be expected from its ionic radius by comparison with...
alkali metal ions. Therefore, the results with NH₄ and Tl emphasize the importance of molecular binding in addition to electrostatic interaction and/or steric hindrance in determining the selectivity of a site. The more complete cationic selectivity of this site would then be: Li ≈ Na > Tl > NH₄ ≈ K > Rb > Cs.

From the results shown in Tables I and II, it appears that, of the alkali metal ions, only Na and Li are translocated. The results with NH₄ and Tl are, however, more difficult to interpret since these cations appear to contribute to the $I_{sc}$ under certain conditions. It is noteworthy that their contributions to the $I_{sc}$ are amiloride insensitive, which would suggest ionic movement through a pathway parallel to that of Na entry. It is somewhat baffling why NH₄ contributes to the $I_{sc}$ in only part of the experiments. The complex behavior of Tl, on the other hand, is hardly surprising given the multiple (including toxic) effects it has in other preparations such as frog myelinated nerve (Hille, 1972), the squid axon (Landowne, 1975), starfish eggs (Hagiwara et al., 1977) and gramicidin A channels (Neher, 1975; Eisenman et al., 1978). It is possible that some of the observed effects of Tl are due to its ability to form neutral complexes with Cl and NO₃, which may be permeable through the apical border. Once present in the cytoplasm, Tl could cause multiple effects. The initial amiloride-sensitive inhibition of $I_{sc}$ caused by Tl has been utilized in the analysis of selectivity for the Na binding site; however, the transient increase in amiloride-insensitive $I_{sc}$ does not provide any information regarding the properties of the actual translocation step. On the basis of these considerations, it will be assumed that the entry site allows the translocation of only Li and Na.

The sharper selectivity of translocation as compared with binding may represent the presence of a higher field strength site or a steric effect restricting entry to cations with dehydrated radii less than about 1.2 Å (Fig. 2). The observed translocation selectivity could also reflect a mechanism involving a conformational change occurring at the entry site when the appropriate ion is present.

It is important to evaluate the extent to which changes in membrane potential across the apical border might affect the $I_{sc}$ in the total replacement experiments. Nagel (1977b) found that the intracellular potential became more negative as external Na was substituted with either choline or K. This is the direction opposite to what would be expected if the inhibitory action of K were exerted through this potential. In addition, alterations in the potential would cause changes in the maximal translocation rate at high [Na]o, which is not observed with K. Similar considerations apply to the other impermeant replacement cations, although intracellular potentials have reportedly not been measured with them in the external solution. Therefore, it is unlikely that membrane potential is important in evaluating this inhibitory action.

One of the consequences of a model which restricts the translocation site to only a fixed number of ions at a time is that it can explain the reported observations of Na transport inhibition by increased cytoplasmic Na concen-
tation in frog skin and other epithelia (Cuthbert and Shum, 1977; Turnheim et al., 1978). Postulating a binding site for Na from the cytoplasmic side would accomplish this, since Na binding to that internal site could inhibit Na entry.

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REFERENCES


