Sodium Channel, Sodium Pump, and Sodium-Calcium Exchange Activities in Synaptosomal Plasma Membrane Vesicles*

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Two mechanisms of Na+ influx have been observed using synaptosomal plasma membrane vesicles purified by density gradient centrifugation from a synaptosomal hypotonic lysate. First, a 5-fold increase in uptake over basal Na+ entry occurs with 60 mM veratridine. The veratridine-dependent Na+ uptake is partially inhibited by 2 mM tetrodotoxin with an apparent time dependency of action (half-maximal inhibition in approximately 20 min). Second, a larger Na+ accumulation (approximately 15-fold above basal) was observed with 2.5 mM ATP, this effect being dependent on internal K+ loading of vesicles although inhibited by high external K+. The two uptake processes are believed to represent operation of the plasma membrane voltage-sensitive Na+ channel, and the Na+-pumping (Na++K+)-ATPase, respectively. Both Na+ flux mechanisms appear to operate in a single population of vesicles since opening of the Na+ channel with veratridine diminishes the ATP-dependent accumulation of Na+ by over 75%. An inverted orientation of the plasma membrane vesicles is likely to account for the functioning of the ATP-dependent Na+ pump and may also account for the low sensitivity and time dependency of the inhibitory action of tetrodotoxin on Na+ channel-opening. Na+ accumulated by the Na+ pump was rapidly effluxed by 10 mM external Ca2+ via the Na+-Ca2+ exchange mechanism which (together with an ATP-dependent Ca2+-accumulating mechanism) was recently characterized in the vesicles (Gill, D. L., Grollman, E. F., and Kohn, L. D. (1981) J. Biol. Chem. 256, 184-192). This result, together with the observed inhibition of Ca2+ influx via (Na+-Ca2+)-exchange due to veratridine-mediated Na+ flux, strongly suggests that the Na+ pump, Na+ channel, and both Ca2+ transport mechanisms function in a single population of inverted plasma membrane vesicles.

The synaptic plasma membrane contains several key ionic flux mechanisms which ultimately modulate the level of intracellular Ca2+ essential to the coupling of depolarization with neurotransmitter release (see Refs. 1 and 2). The influx and efflux of Ca2+ ions across the membrane is intimately associated with changes in the flux of Na+ ions (2-4). Thus, both the Na+ gradient and the resting membrane potential arising from the function of the Na+ pump are driving forces for the extrusion of Ca2+ via the electrogenic Na+-Ca2+ antipporter (3-5). The depolarization arising from Na+ conductance via Na+ channels facilitates the influx of Ca2+ through voltage-sensitive Ca2+ channels (2, 3, 5). Also, internal Na+ may consider-

ably modify the efflux of Ca2+ ions via an ATP-dependent Ca2+ pump mechanism (6). Therefore, analysis of the Na+ flux mechanisms of the synaptic plasma membrane has important consequences to determining the control of Ca2+-mediated excitation-release coupling in the nerve terminal.

Using a preparation of synaptosomal membrane vesicles, the Ca2+ transport mechanisms believed to originate from the plasma membrane were recently characterized in detail (6). By "flux-reversal" procedures, the two major Ca2+ fluxes (Na+-Ca2+-exchange and ATP-dependent Ca2+ transport) were demonstrated to coexist within a single population of vesicles within this preparation. Since Na+-Ca2+ exchange is known to operate across the squid axon membrane (7) and outer synaptosomal membrane (8, 9), both vesicle activities were suggested to originate from the synaptic plasma membrane (4, 6).

The present report identifies some parameters of Na+ transport across the same vesicle membranes which are characteristic of those fluxes associated with the plasma membrane. Thus the vesicles contain a veratridine-sensitive Na+ channel, and an (ATP + K+)-dependent Na+ transport mechanism. The function of both Na+ transport systems suggests they are operating in a single population of inverted plasma membrane vesicles. Furthermore, Ca2+-dependent flux-reversal of Na+ accumulated by the Na+ pump indicates that this mechanism operates in the same population of vesicles as the Na+-Ca2+ exchanger, supporting the contention that both the previously characterized Ca2+ transport mechanisms also operate in the plasma membrane.

EXPERIMENTAL PROCEDURES

Preparation of Synaptosomal Plasma Membrane Vesicles—Vesicles were isolated from guinea pig cerebral cortex as described previously (6). This method involved isolation of synaptosomes followed by hypotonic lysis based on the procedure of Kanner (10). Experiments on Na+ flux described in this report used a fraction further purified by sucrose-density gradient centrifugation and referred to as "light membrane vesicles" (6). This fraction corresponds closely to the synaptic plasma membrane fraction characterized in detail by Cotman (11), and is subsequently referred to in this report as synaptosomal plasma membrane vesicles or vesicles.

The vesicles were finally resuspended in 0.32 mM sucrose, 1 mM K+ EDTA, pH 7.4, and stored in liquid nitrogen at a concentration of 0.6 mg of membrane protein/ml. Vesicles contained an internal volume of approximately 1 μl/mg under experimental conditions.

Na+ Flux Experiments—For Na+ influx studies, 100-μl aliquots of synaptosomal plasma membrane vesicles (0.6 mg of protein) were thawed at room temperature and diluted with 1.3 ml of pre-equilibrium medium (150 mM KCl, 1 mM MgCl2, 5 mM HEPES (KOH, pH 7.4) for 10 min at 37 °C. The vesicles were then centrifuged (15,000 x g, 5 min) and the pellet resuspended with 300 μl of pre-equilibrium medium. Na+ uptake commenced upon addition of 5 μl of resuspended

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1 The abbreviations used are: MOPS, 4-morpholinepropanesulfonic acid; EGTA, ethylene glycol bis(β-aminooethyl ether)-N,N,N',N'-tetraacetic acid.
vesicles (approximately 15 µg of protein) to 100 µl of external medium containing 140 mM choline chloride, 5 mM MgCl₂, 0.2 mM EGTA, 5 mM MOPS-Tris, pH 7.4, 1 mM NaCl with 0.01 Ci/mmol of ²²Na (approximately 500,000 cpm/tube) together with those additions described in the figures. After the appropriate period of uptake at 25 °C, influx was terminated by rapid addition of 2.0 ml of ice-cold 150 mM choline chloride, 5 mM MgCl₂, 0.2 mM EGTA, 5 mM MOPS-Tris, pH 7.4. Na⁺ uptake commenced on addition of 50 µM veratridine (13). This uptake was inhibited at least partially by tetrodotoxin, the specific blocker of Na⁺ channel function in neural membranes (14). However, it was noted that the veratridine-dependent Na⁺ accumulation was considerably less sensitive to tetrodotoxin than has generally been reported for neural tissues where concentrations in the nanomolar range are normally effective (see Ref. 15). Two explanations were possible for the noncomplete action of tetrodotoxin. First, the veratridine-sensitive Na⁺-accumulating vesicles may be heterogeneous with regard to sidedness resulting in only a fractional sensitivity to tetrodotoxin. Alternatively, the likely inverted nature of the vesicles previously (6) and subsequently alluded to, may alone account for their relative insensitivity to tetrodotoxin. It is known that the low hydrophobicity of the toxin molecule precludes an effect on its external site of action when administered, for example, internally to dialyzed squid axons (16). The internally oriented active sites of inverted vesicles might be similarly inaccessible to tetrodotoxin. However, as seen in Fig. 1, although tetrodotoxin at 2 µM inhibited the veratridine effect by approximately 50% after 30 min, it was noted that after only 5 min little inhibition had occurred. This increased effectiveness of tetrodotoxin with time could represent a slow or partial entry of the toxin molecule into inverted vesicles. Such an interpretation of the effect of tetrodotoxin is strengthened by examining the effects of preincubating vesicles with tetrodotoxin prior to their addition to the uptake medium containing ²²Na and veratridine (Table I). In this experiment, 2 µM tetrodotoxin inhibited veratridine-dependent Na⁺ accumulation by no more than 25% when present only during the 10 min uptake in the presence of 50 µM veratridine. However, when added to vesicles during a 20- or 40-min preincubation, tetrodotoxin caused a proportionately greater decrease in veratridine-dependent Na⁺ uptake. After 40 min of preincubation, tetrodotoxin caused almost a 60% reduction of the subsequent veratridine-mediated accumulation of Na⁺. These results suggest an abnormally slow time dependence of the effect of tetrodotoxin which may be associated with its slow access to an internal site of action. The data do not, however, totally exclude the possible existence of noninverted vesicles. Other reports using brain membranes (17) or unpurified vesicles (18) have indicated a more rapid tetrodotoxin reversal of Na⁺ channel opening, the difference probably arising from the relative fractions of right-side out vesicles in the various preparations. The relatively rapid action of veratridine in the present experiments may imply an action on the external surface (originally internal) of inverted vesicles, although the lipid solubility of the molecule (19) would facilitate its passage into vesicles even if this were not the case. Another implication for the effect of veratridine on inverted vesicles would be the bidirectionality of Na⁺ conductance through the Na⁺ channel.

In addition to the function of this apparent Na⁺ channel, vesicles also accumulate Na⁺ in the presence of ATP, an activity which more convincingly characterizes their plasma membrane origin and inverted orientation. In this case, using 2.5 mM ATP, the uptake of Na⁺ above basal equilibration was approximately 3-fold greater than in the presence of 50 µM veratridine (Fig. 2). Unlike the effect of the latter agent, the ATP-mediated Na⁺ accumulation was dependent on pre-equilibration of the vesicles in K⁺-containing medium. Use of pre-equilibration medium (which determines the internal ionic composition of vesicles) containing 150 mM LiCl or choline chloride, or use of KCl in the external as well as pre-equilibration media, in either case precluded significant ATP-dependent Na⁺ accumulation in vesicles (data not shown). Thus the effect of ATP was dependent on internal K⁺ and either mediated by an outward K⁺ flux or simply inhibited by...
Plasma membrane vesicles. The ineffectiveness of 0.2 mM both suggest that the Na⁺ pump is functioning in inverted ATP other plasma membranes. Furthermore, the accessibility of pumps Na⁺ in exchange for K⁺ in the neural (20) as well as external K⁺. The ATP and K⁺ dependence of this Na⁺ flux details of the vesicle preparation and procedures for determining Na⁺ by addition of cold choline chloride and rapid filtration. For each 100 pl of external medium and was terminated after the specified time to together with either 140 mM choline chloride, 5 mM MgCl₂, 0.2 mM EGTA, 5 mM MOPS-Tris, pH 7.4, 1 mM NaCl (with 0.01 Ci/mmol of 2Na) together with 50 μM veratridine. Tetra- dioxide in the uptake medium, either added directly (B), or derived from the vesicle preincubation (C and D), was present at 2 μM. Uptake for all determinations was for 10 min at 25 °C and was terminated by dilution and rapid filtration. Details of the Na⁺ uptake procedures are described under "Experimental Procedures." Each result is the mean ± standard deviation of triplicate determinations with basal Na⁺ uptake in the absence of veratridine subtracted.

Table I

<table>
<thead>
<tr>
<th>Incubation conditions for sodium uptake</th>
<th>Sodium uptake above control</th>
<th>Sodium of verat- line control</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Veratridine</td>
<td>4.06 ± 0.63</td>
<td>100.0</td>
</tr>
<tr>
<td>B. Veratridine + TTX (no preincubata- tion)</td>
<td>3.03 ± 0.57</td>
<td>74.6</td>
</tr>
<tr>
<td>C. Veratridine + TTX (20-min preincuba- tion)</td>
<td>2.50 ± 0.23</td>
<td>61.6</td>
</tr>
<tr>
<td>D. Veratridine + TTX (40-min preincuba- tion)</td>
<td>1.74 ± 0.14</td>
<td>42.8</td>
</tr>
</tbody>
</table>

FIG. 2. Na⁺ accumulation by synaptosomal plasma membrane vesicles via Na⁺ pump or Na⁺ channel activities. Pre- equilibration of vesicles was in 150 mM KCl, 1 mM MgCl₂, 5 mM MOPS-KOH, pH 7.4, 10 min at 37 °C. The external medium contained 140 mM choline chloride, 5 mM MgCl₂, 0.2 mM EGTA, 5 mM MOPS-Tris, pH 7.4, 1 mM NaCl (with 0.01 Ci/mmol of 2Na) together with either 50 μM veratridine (B) or 2.5 mM ATP (C). Uptake at 25 °C was started by addition of 5 μl of pre-equilibrated vesicles to 100 μl of external medium and was terminated after the specified time by addition of cold choline chloride and rapid filtration. For each determination, basal uptake measured in the absence of veratridine or ATP has been subtracted. See "Experimental Procedures" for details of the vesicle preparation and procedures for determining Na⁺ uptake.

External K⁺. The ATP and K⁺ dependence of this Na⁺ flux are indicative of the action of the (Na⁺ + K⁺)-ATPase which pumps Na⁺ in exchange for K⁺ in the neural (20) as well as other plasma membranes. Furthermore, the accessibility of ATP to its site of action and the direction of the Na⁺ flux both suggest that the Na⁺ pump is functioning in inverted plasma membrane vesicles. The ineffectiveness of 0.2 mM ouabain in the uptake medium on inhibiting the (ATP + K⁺)-dependent Na⁺ accumulation (data not shown), is explained by the lack of access of this specific inhibitor to its site of action on the inner surface of the Na⁺-accumulating vesicles, which originally existed on the outer surface of the neural plasma membrane (21).

Although both the veratridine-sensitive Na⁺ channel activity and the (ATP + K⁺)-dependent Na⁺ pump activity are believed to originate from a single source (the plasma membrane), it was possible to substantiate this premise using a "flux-reversal" procedure. Thus, as shown in Table II, 50 μM veratridine added together with 2.5 mM ATP inhibited more than 75% of the ATP-dependent component of Na⁺ accumulation. The subtractivity of the simultaneous effects of both agents on Na⁺ uptake is highly suggestive of their combined action in a single population of vesicles which, by virtue of the nature of the Na⁺ flux mechanisms, almost certainly originate from the plasma membrane. The reversal of Na⁺ pump activity by veratridine is consistent with the expected action of the two mechanisms whereby the Na⁺ gradient created by the active ATP-dependent mechanism is dissipated by the passive diffusion of Na⁺ through the opened nondirectional Na⁺ channel.

In previous studies, it has been suggested that both the ATP-dependent Ca²⁺ transport and Na⁺-Ca²⁺ exchange mechanisms, which functioned in a single population of vesicles, were derived from the plasma membrane. This inference was drawn mainly from the evidence that Na⁺-Ca²⁺ exchange is known to operate in the neural plasma membrane (7–9). However, using similar "flux-reversal" methods, it has been possible to directly establish that the Na⁺-Ca²⁺ exchange mechanism functions in the same vesicles as those containing the Na⁺ pump and Na⁺ channel activities, further substantiating the plasma membrane origin of both Ca²⁺ flux mechanisms. First, veratridine, which permits Na⁺ entry into the vesicles (Fig. 1), also inhibits the entry of Ca²⁺ mediated by Na⁺-Ca²⁺ exchange (that is, an outwardly directed Na⁺ flux; see Ref. 6) presumably by dissipating and "competing" for the Na⁺ gradient in the vesicle. Second, Na⁺ accumulated by the (ATP + K⁺)-dependent pump mechanism is effluxed upon addition of Ca²⁺ to the external medium (Fig. 3). In this experiment, 10 mM CaCl₂ was added to vesicles after maximal accumulation of Na⁺ in the presence of 2.5 mM ATP and an outward K⁺ gradient. The rapidity of the Ca²⁺-dependent reversal of Na⁺ accumulation suggests that a mediated efflux of Na⁺ is occurring rather than an indirect action of Ca²⁺ on membrane permeability resulting from, for example, activa-
Fig. 3. Ca\(^{2+}\)-dependent reversal of Na\(^+\) pump-mediated Na\(^+\) accumulation in synaptosomal plasma membrane vesicles. Uptake of Na\(^+\) commenced upon addition of 5 \(\mu\)l of vesicles pre-equilibrated for 10 min at 37°C in 150 mm KCl, 1 mm MgCl\(_2\), 5 mm pH 7.4, 100 mm of external medium (40 mm choline chloride, 5 mm MgCl\(_2\), 0.2 mm EGTA, 5 mm MOPS-Tris, pH 7.4, 1 mm NaCl with 9.0 mmol of \(\gamma\)-Na\(^+\)) either with (C) or without (D) 2.5 mm ATP (Tris salt). Uptake was terminated after the appropriate time at 25°C by addition of 2.0 ml of ice-cold 150 mm choline chloride followed by rapid filtration. Tubes incubated 15 min or longer received either 10 \(\mu\)l of external medium (C, D) or 10 \(\mu\)l of external medium containing 100 mm CaCl\(_2\) instead of choline chloride (D) giving a final Ca\(^{2+}\) concentration of approximately 10 mm. These additions were made 15 min after Na\(^+\) uptake began. For the 15-min time points, the additions were made rapidly by dilution and filtration. Details of the conditions for incubation and filtration are given in "Experimental Procedures."

Fig. 4. Diagrammatic representation of the Na\(^+\) and Ca\(^{2+}\) flux mechanisms observed in inverted synaptosomal plasma membrane vesicles. Experimental evidence for the function of (1) ATP + Mg\(^{2+}\)-dependent Ca\(^{2+}\) transport, (2) Na\(^+\)-Ca\(^{2+}\) exchange, and (3) possible voltage-sensitive Ca\(^{2+}\) channel activity, is described in Ref. 6. As detailed in this report, the vesicles also accumulate Na\(^+\) via 4) a veratridine-sensitive Na\(^+\) channel, and 5) an (ATP + K\(^+\))-dependent Na\(^+\) pump mechanism. Evidence to suggest the function of these mechanisms in a single population of inverted plasma membrane vesicles and details of the characteristics of the flux mechanisms are described in the text.

**References**


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