Analysis of Sodium and Potassium Redistribution during Sustained Permeability Increases at the Innervated Face of *Electrophorus* Electroplaques

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ABSTRACT   Cholinergic agonists cause an increase in the membrane permeability to Na and K at the innervated face of *Electrophorus* electroplaques. Therefore, sustained exposure to agonist reduces Na and K concentration gradients. These gradients are monitored with voltage-clamp sequences and pharmacological treatments that selectively measure the Nernst potentials for individual ions. E_K is normally near -90 mV but moves toward zero during bath application of agonist. Depolarizations by bath-applied agonist measure primarily this shift of E_K, not short-circuiting of E_K by the agonist-induced conductance. After a rapid jump of agonist concentration, there is a fast (millisecond) depolarization due to the conductance increase, followed by a much slower additional "creep" due to the shift in E_K. Sodium replaces the lost intracellular potassium: E_{Na}, normally very positive, also moves toward zero. The shifts in E_K and E_{Na} are normally reversible but become permanent after blockade of the Na-K pump. In the presence of agonist, the shifts can be driven further by passing current of the appropriate polarity. Similar ion redistribution occurs with other drugs, such as batrachotoxin and nystatin, which induce prolonged increases in Na permeability. The redistributions cause little net change in the reversal potential of the neurally evoked postsynaptic current.

INTRODUCTION

When nicotinic agonists are applied to *Electrophorus* electroplaques, a reversible depolarization occurs (Schoffeniels and Nachmansohn, 1957; Higman et al., 1963). Such depolarizations are often used as a measure of acetylcholine receptor activation. These analyses are based on the assumption that the depolarization occurs because the agonist-induced conductance short-circuits the resting potential.

This assumption can be tested using the dissection and chamber for single electroplaques introduced by Schoffeniels (1957). The innervated face is held against a thin plastic sheet that partitions two pools of Ringer's solution; part of the innervated face is exposed to one of the pools through a window in the sheet. There is little current flow around the edge of the window; thus, when agonist is applied to the innervated face, only this face should depolarize. Karlin

(1967), however, observed that when agonist was present in the solution bathing the innervated face, the non-innervated face depolarized almost as much as the innervated face. This effect was much larger than expected from residual current flow between the two faces, and the depolarization became permanent in the presence of ouabain. Karlin therefore suggested that Na replaced internal K during the prolonged permeability increase; the change in E_K would cause the depolarization across the non-innervated face. Lester et al. (1975) studied current-voltage (I-V) relations of the innervated face and found that bath-applied agonists produced two reversible effects: (a) a conductance increase, and (b) a "shift" toward more positive voltages in the I-V plot of the nonsynaptic membrane. These observations supported Karlin's hypothesis that E_K changes.

Experiments with bath-applied agonist have yielded new information on acetylcholine receptors in *Electrophorus* electroplaques (Ruiz-Manresa and Grundfest, 1971; Sheridan and Lester, 1975, 1977; Lester and Chang, 1977; Lester et al., 1975, 1978). In extending these experiments it would be helpful to decide whether this treatment causes redistribution of ions. Furthermore, such redistribution could provide a convenient means of controlling internal ion concentrations. I have therefore re-examined the Nernst potentials across the innervated face, with a view toward testing the following predictions of Karlin's hypothesis. (a) The shift in the I-V plot (Lester et al., 1975) should become permanent when the Na-, K-activated ATPase is blocked. (b) As Na replaces internal K, E_{Na} should move toward zero. (c) The shift should be enhanced by loading the cell with Na during current flow of the appropriate polarity. (d) The response to a photic "concentration jump" of agonist (Lester and Chang, 1977) should be a rapid depolarization due to the short-circuiting, followed by a slower depolarizing "creep" due to the redistribution. (e) The shift should be produced by other agents that cause a prolonged increase in the Na permeability. These predictions have been confirmed, as briefly reported (Lester, 1977).

We clarify certain electrochemical terms. For an individual ion, the Nernst or equilibrium potential is well defined as a zero-current potential for that ion. A single conductance pathway or group of pathways may involve more than one ion but still have a zero-current or reversal potential (i.e., G_l and E_l in Fig. 1). The membrane as a whole has a zero-current potential, regardless of whether agonists or other drugs are present, where the I-V plot intersects the V-axis. At any given time, this zero-current potential of the membrane is a "resting" potential.

METHODS

The experiments employ single, isolated electroplaques from the organ of Sachs of *Electrophorus electricus*. Animals were maintained in the laboratory as previously described (Sheridan and Lester, 1977) for at least 2 wk before the experiments. Cells from newly arrived animals often had low resting potentials and feeble responses to agonist.

The voltage-clamp arrangements have been described (Sheridan and Lester, 1977). The transcellular method of voltage-sensing has several advantages of speed and stability. However, with this method one must assume that zero-current potentials do not change during the clamp episodes. Inasmuch as this point is central to the studies, it was verified under the present experimental conditions (to within 2 mV) for episodes <0.5 s duration. Therefore, the transcellular method was used for such trials, including the "ramp-

clamps" (the ramp speed was ± 1 mV/ms). For clamps lasting longer than 0.5 s, however, the transmembrane arrangement (Nakamura et al., 1965; Lester et al., 1975) was used (e.g., the experiments of Fig. 7). During such long clamps the usual PT plate electrodes for passing current polarized too strongly; they were replaced by spirals of chlorided silver wire.

Electrically excitable Na currents were measured with the "single trial" method (Sheridan and Lester, 1977). Each clamping episode consisted of both a hyperpolarizing jump which yielded capacitative and leakage currents, and a depolarizing jump which produced Na currents as well. Currents from the two jumps were scaled appropriately and added (Sheridan and Lester, 1977). "Notches" often appeared on the current records for command voltages in the region of negative slope conductance, indicating that cells were probably not well space-clamped in this range of potential. This is not a problem in the present studies because attention is focused on the region of maximal Na activation and on the Na equilibrium potential. Na activation kinetics depended strongly on temperature between 9° and 23°, although contrary conclusions were drawn from a study using less direct measurements (Ruiz-Manresa and Grundfest, 1976).

Pools A and B bathe the innervated and non-innervated face, respectively. The standard Ringer's solution contained NaCl, 160 mM; KCl, 2.5 mM; $CaCl_2$, 2 mM; $MgCl_2$, 2 mM; Na-Hepes, 10 mM (pH 7.2). For experiments on the reversal potential of neurally evoked postsynaptic currents (PSCs), pool A contained prostigmine (10 μM), because PSC reversals are more often observed in the presence of this drug (Sheridan and Lester, 1977). For experiments using strophanthidin or batrachotoxin, the drug was first dissolved in ethanol, then diluted to the appropriate final concentration in Ringer solution. Therefore, ethanol (0.5) was present in the Ringer solution; this concentration had no effects by itself. Organic chemicals were obtained from Sigma Chemical Co., St. Louis, Mo.

The experiments were controlled and analyzed by a minicomputer (Nova 2/10, Data General Corp., Westboro, Mass.). Some details have already been given (Sheridan and Lester, 1977). The on-line program is written in BASIC with machine-language subroutines that control the analog and digital interfaces to the experiment. The program controls each voltage-clamp trial with reference to an array of forty parameters; these parameters specify (a) the waveform of the command voltage, (b) progressive modifications to this waveform in successive clamping episodes, (c) number of episodes, (d) sampling intervals, and other features of the experiment. There are three such arrays. One-letter commands modify parameters or commence a trial. With this arrangement it was possible to switch rapidly among trials that selectively isolated either agonist-induced conductances (Lester et al., 1975), PSCs (Sheridan and Lester, 1977), or Hodgkin-Huxley sodium currents (Hodgkin and Huxley, 1952). Digitized data are stored on cassette tapes and floppy disks. Preliminary analyses are performed on-line and traces such as those in Results appeared on the X-Y scope.

ELECTRICAL EQUIVALENT CIRCUIT

The strategy of these experiments was to apply pharmacological agents and voltage-clamp sequences that selectively measure the Nernst potentials for individual ions and the reversal potential of the leakage pathway. Grundfest and his colleagues have established the electrical parameters of the membrane of the innervated face. Their work may be summarized by Fig. 1 (Nakamura et al., 1965; Morlock et al., 1968; Ruiz-Manresa, 1970; Ruiz-Manresa et al., 1970; Ruiz-Manresa and Grundfest, 1971). The synaptic conductance G_S is shown as a single pathway in series with a reversal potential E_S. It now seems preferable to

use this formalism rather than to show separate K and Na pathways connected by a common switch (Ruiz-Manresa and Grundfest, 1971), because the two ions flow through the same channels (Dionne and Ruff, 1977). The electrically excitable pathway, G_{Na}, produces the electric organ's discharge. There is little or no delayed K rectification in gymnotid electroplaques. The anomalous rectifier is represented by G_K; in most of these experiments G_K was eliminated with 3 mM Ba. The ohmic leakage pathway, G_l, is usually described as a K conductance; but it may have a minor contribution from Cl (see below). Therefore, I refer to its reversal potential as E_l.
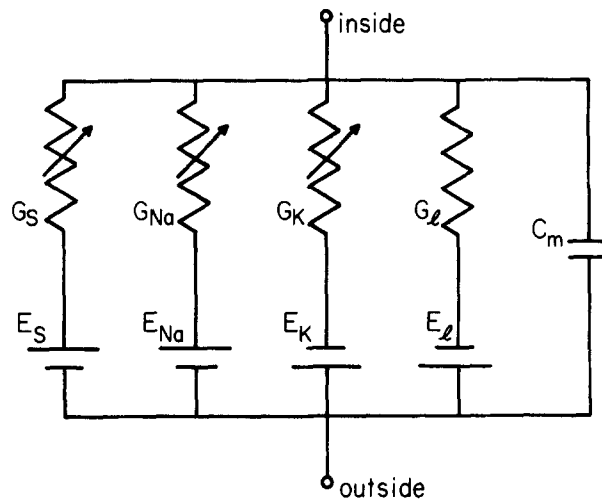

FIGURE 1.   Equivalent circuit of the innervated face. See text for details.

RESULTS

Recapitulation of the "Shift" in E_l Produced by Nicotinic Agonists

The electrically excitable conductance G_{Na} inactivates with sustained depolarization (Hodgkin and Huxley, 1952; Nakamura et al., 1965). Therefore, during slow "ramp clamps" the membrane conductance is $G_S + G_l$ (Lester et al., 1975). Fig. 2 presents an experiment based on this idea. When carbachol was added to pool A, the agonist-induced conductance, G_S, increased and eventually equaled about 60 mmho/cm² (slope conductance) at -100 mV. Furthermore, G_S depends on voltage and becomes very small at positive potentials (Ruiz-Manresa and Grundfest, 1971; Lester et al., 1975). Therefore, in this region only E_l and G_l determine the current-voltage relation, and G_l is not changed by agonist (Fig. 2). The value of E_l is given by extrapolating the I-V plot at positive voltages to zero current (Lester et al., 1975). It is a key observation that bath-applied agonist drives both the zero-current potential and E_l toward zero, and to nearly the same extent. Therefore, the depolarization does not provide a direct measure of how the agonist-induced conductance (G_S) short-circuits the resting potential E_l. Instead the depolarization mostly measures a shift in E_l, the zero-current potential of the nonsynaptic membrane.

The shift in E_l is measured when any bath-applied agonist increases the conductance of the innervated membrane. If depolarizations are measured, the dose-response relation is that of the shift rather than that of the agonist-induced conductance (Lester et al., 1975). The shift is reduced by agents that block G_S, such as curare, the elapid α-toxins, and some local anesthetics (Koblin and Lester, 1978).
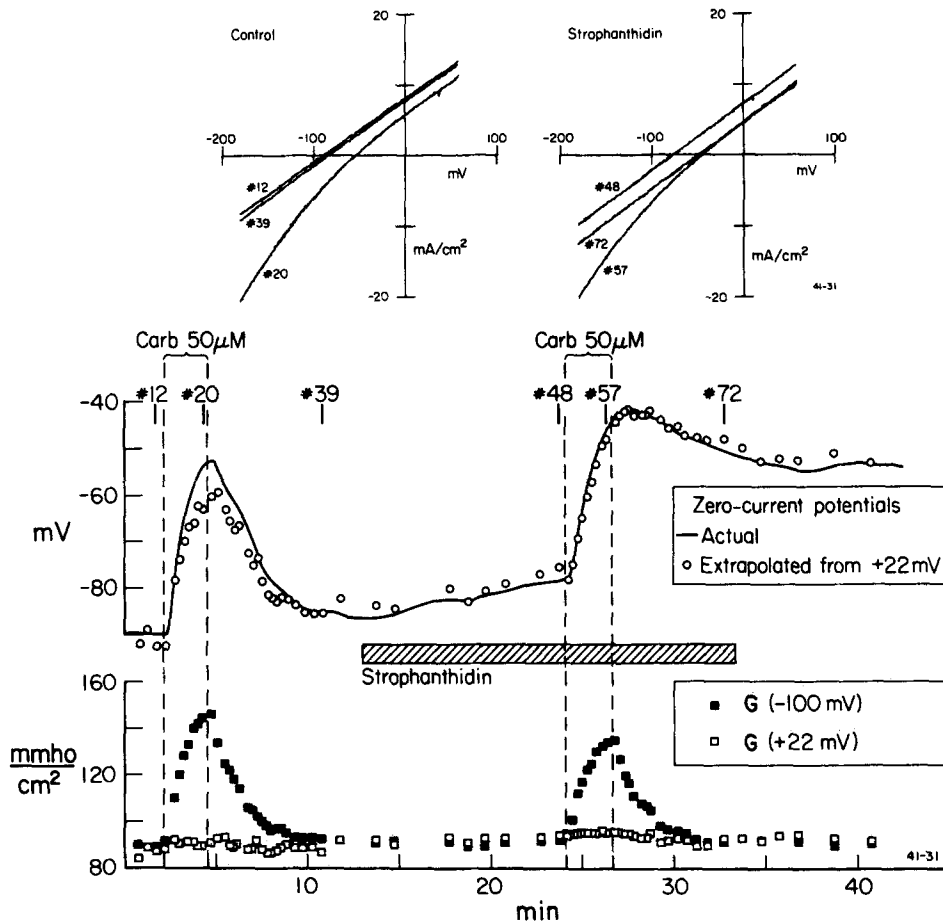

FIGURE 2.   The shift in G_l upon bath application of Carb. Upper panel: *I-V* plots for some of the trials. Middle panel: potentials as a function of time. Solid line is actual zero-current potential; (O) values for E_l, obtained by extrapolation from +22 mV. See text. Times are indicated for trials shown in upper panel. Lower panel: slope conductances at two different voltages. Strophathidin (0.5 mM) was present in pool B for the indicated period.

When the agonist is removed from pool A, the shift usually recovers more slowly than does G_S. This effect is less noticeable than usual in Fig. 2 because agonist was washed in and out slowly in order to provide many time points. In a more typical experiment (Fig. 6) the bulk solution chage is complete within 10

s; G_S returns to zero within a half-time of 30–60 s; and E_l recovers about five times more slowly.

After several exposures to agonist, E_l recovers slowly and only partially. Recovery can be blocked completely with inhibitors of the Na pump such as ouabain (Karlin, 1967) or strophanthidin (Fig. 2). At the concentration used (0.5 mM) strophanthidin renders the shift permanent whether it is added to pool A (bathing the innervated face) or to pool B (bathing the noninnervated face). By contrast, G_S is only slightly affected by repeated agonist application or by inhibitors of the sodium pump.

"Instantaneous" I-V Relation of G_l

The shift can also be measured by a method that does not require extrapolating the I-V plot. The membrane potential is first clamped to a positive value, usually between +50 and +100 mV, where few if any acetylcholine receptor channels are open. The voltage is then jumped to a more negative value. Immediately after the jump, only G_l is present. At low temperatures the membrane capacitance is charged completely before G_S, the agonist-induced conductance, becomes appreciable (see Fig. 3 in Sheridan and Lester, 1977). Thus, the "instantaneous" I-V plot has a slope and V-intercept given by G_l, respectively. In each of several dozen cells examined, these measurements agree quantitatively (±5%) with values obtained by extrapolating the equilibrium I-V plot as described above.

G_l is mostly a Potassium Conductance

If only depolarizations are measured, the shift in E_l distorts or completely masks measurements of desensitization (Lester et al., 1975). In frog muscle fibers the membrane potential also gives an inaccurate measure of desensitization, primarily owing to rapid redistribution of Cl (Hodgkin and Horowicz, 1959; Jenkinson and Terrar, 1973). It was therefore relevant to determine the contribution of Cl to G_l.

Current-voltage relations were measured in 13 mM chloride solution (7.5% of normal). The clearest results were seen when glutamate was substituted for Cl. There was a small decrease in G_l (<20%). There was no detectable diminution (<20%) in the shift. Sulphate, methanesulfonate, and isethionate were also used as Cl substitutes; however, because these ions precipitate Ba, the I-V relations had to be measured in the presence of G_K. Nonetheless, at positive potentials these more complex I-V relations could still be extrapolated to show the shift in the zero-current potential of the nonsynaptic membrane.

The shift was seen after as long as 5 h in these 13 mM Cl solutions. Furthermore, the shift was still rendered irreversible by simultaneous exposure to ouabain and agonists. However, with low-Cl solutions small repolarizations (1–3 mV) were sometimes observed during desensitization (c.f. Jenkinson and Terrar, 1973). These observations agree with previous reports that *Electrophorus* electroplaques have low Cl conductance (Altamirano and Coates, 1957; Higman et al., 1964; Nakamura et al., 1965; Karlin, 1967). In summary , E_{Cl} could change

during the shift, but the chloride conductance contributes very little to the *I-V* relations.

The Shift in E_l Is Accompanied by a Shift in E_{Na} but No Change in E_S

The experiment of Figs. 3–6 was devised to reveal simultaneous changes in E_{Na}, E_l, and E_S during bath application of Carb. Fig. 3 shows that E_l is shifted by ~25 mV in the positive direction as already described. Electrically excitable currents reverse at about E_{Na}, and Fig. 4 shows that E_{Na} underwent a reversible shift of

Figure 3. *I-V* plots like that of Fig. 2 taken before, during, and after bath application of Carb. See Fig. 6 for summary of the entire experiment.

about 50 mV toward zero. All experiments of this type showed larger shifts in E_{Na} than in E_l, as expected from the limitation of the internal volume and the initial low value of internal [Na]. A more detailed comparison has not been attempted in view of the uncertainties about adequate space-clamp and about compensation for series resistance. However, the large shift in E_{Na} supports the argument that the observed changes result from alterations in internal ion concentrations rather than in external compartments that might exchange slowly with the bulk solution.

Because acetylcholine receptor channels are permeable both to Na and K (Ruiz-Manresa and Grundfest, 1971; Lassignal and Martin, 1977), these opposite changes in E_K and E_{Na} should partially cancel each other for measurements of E_S. Indeed for most cells (e.g., Fig. 5) there were no detectable changes in E_S during bath-application of agonist.

It was of interest to identify other effects of bath-applied agonist on the PSC. At low agonist concentrations and potentials in the range of 0 to −50 mV, as in Fig. 5, PSC waveforms are substantially unaffected. This is hardly surprising, because this concentration produces little desensitization, and at these voltages

the agonist-induced conductances are quite small (Lester et al., 1975). However, at positive voltages, where outward current would flow, PSCs are reversibly suppressed during bath-applied agonist (Fig. 5). The effect is small but appears in all cells that have resting potentials more negative than −80 mV at the beginning of the experiment. In partially depolarized cells, one usually does not observe PSC reversals even before adding agonist. These observations suggest
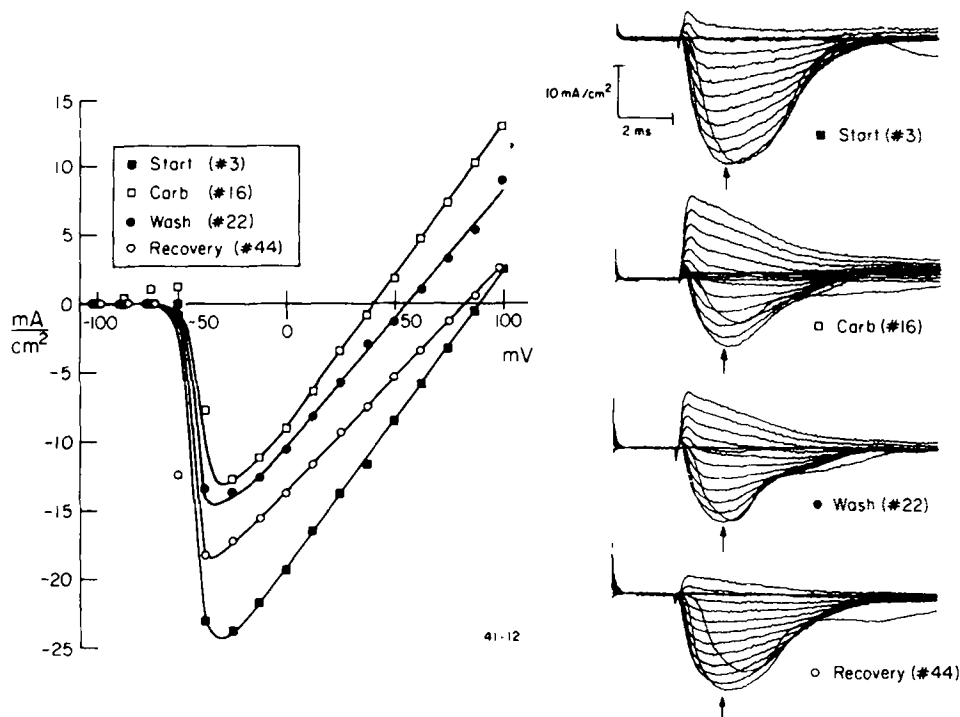

FIGURE 4. Sodium currents before, during, and after bath application of Carb. See Fig. 6 for summary of the entire experiment. Voltage was −90 mV before the depolarizing jump. Isochronous current-voltage plot, measured 1.9 ms (vertical arrows) after depolarizing jump. Gating currents appear in some episodes, particularly in episode at E_{Na} (second trace from top) in trial 3. All the trials have been corrected for leakage currents using the data from trial 3, to avoid contributions from agonist-induced currents. See Methods.

that ACh receptors or their channels are affected by the internal ionic concentrations.

The Shift Can Be Driven Further With Current

In the chamber used for these studies, externally applied currents pass through both faces of the cell. At rest the two faces seem to have the same ionic permeabilities (mostly K); even sustained transcellular currents, therefore, produce little change in internal ion concentrations (Fig. 7, trials 52, 53).

However, agonist induces G_S only at the innervated face. Let us now consider transcellular current which passes inward through this face. Inasmuch as G_S has a component of Na conductance (Ruiz-Manresa and Grundfest, 1971; Lassignal and Martin, 1977), sodium would flow inward at this face, but K would flow outward at the non-innervated face. The expected result, a further shift in E_K, has been observed (Fig. 7, trials 68, 69).

Some trials were conducted in an effort to clamp the cell at positive voltages during agonist application. Presumably the shift would be suppressed both
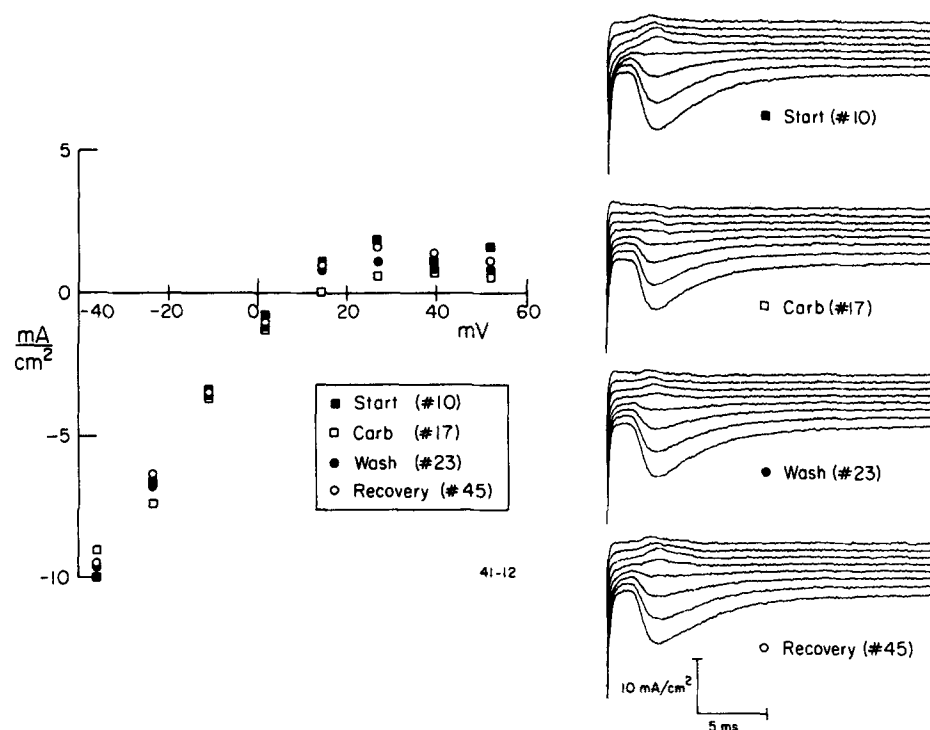

FIGURE 5. Neurally evoked PSCs before, during, and after application of Carb. See Fig. 6 for summary of the entire experiment. Leakage currents have not been subtracted from the traces.

because few receptor channels open at this voltage (Ruiz-Manresa and Grundfest, 1971; Lester et al., 1975), and because there is only a small driving force for Na ions. However, during control experiments without agonist, sustained depolarization reactivated G_K, the anomalous rectifier. Current-voltage relations became complex and time-dependent, vitiating accurate measurements on the shift. Perhaps sustained outward current caused external K to accumulate in the microvesicular tubules on the innervated face; inasmuch as high K can overcome the inhibition of G_K by Ba (Ruiz-Manresa, 1970), the anomalous rectifier again carried current. This unsuccessful experiment does, however, reinforce the conclusion that bath-applied agonist reduces the K concentration

gradient through internal depletion of K rather than through external accumulation: the latter mechanism would reactivate G_K in the experiments of Fig. 2–6, but such an effect was not seen.
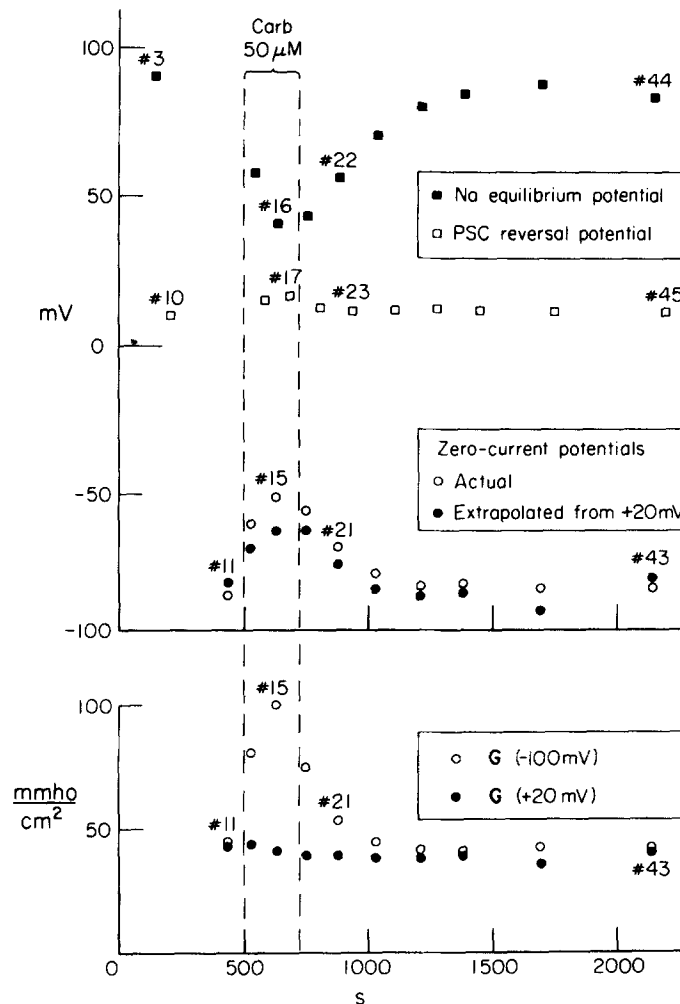
FIGURE 6.   Summary of the data for the experiment of Figs. 3, 4, and 5.

Agonist Concentration Jumps

These experiments were performed using the photochemical *cis→trans* isomerization of 3,3'-*bis*-[α-(trimethylammonium)methyl]azobenzene (Bis-Q; Bartels et al., 1971; Lester and Chang, 1977; Nass et al., 1978). In order to duplicate the conditions of previous dose-response studies using depolarizations (e.g., Higman et al., 1963), membrane potential was recorded without Ba and without externally applied current.

In the experiment of Fig. 8, pool A was first flushed with solution containing 50 nM of the *cis*-equilibrium solution of Bis-Q. This solution contained about 10 nM of the *trans*-isomer, which is an agonist (Bartels et al., 1971; Lester and Chang, 1977). After 2 min there was a nearly stable depolarization of ~15 mV,
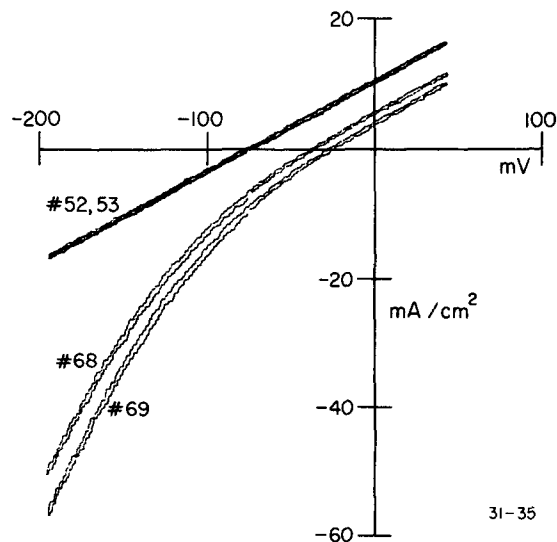

FIGURE 7.   Ramp-clamp trials in the absence (52, 53) and in the presence (68, 69) of Carb (50 μM). After trial 52, the cell was clamped to −100 mV for 20 s. The clamp was then removed and the next trial (53) was taken 3 s later. There was no change in the *I-V* relation. Carbachol (50 μM) was then applied as usual. After 6 min of exposure, the *I-V* relation stabilized with a zero-current potential at −35 mV (trial 68). The cell was again clamped to −100 mV for 20 s, requiring an inward current of about 14 mA/cm². The next voltage-clamp trial (69) revealed a further shift of 12 mV in the *I-V* relation.
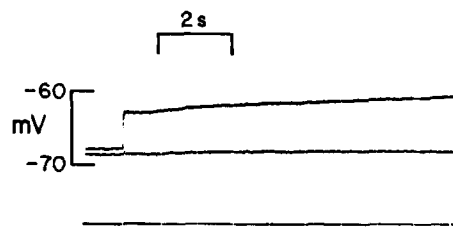

FIGURE 8.   Agonist concentration-jump experiment. Intracellular recording, with reference electrode in pool A (bathing the innervated face). Lower trace shows trigger signal to flashlamp. See text.

shown by the nearly level sweep in Fig. 8. During the next sweep a light flash (duration 0.3 ms) increased the *trans*-Bis-Q concentration to ~23 nM uniformly throughout the chamber. There was a rapid depolarization of 6 mV. The subsequent slower drift, at a rate of ~0.2 mV/s, represents the change in E_t.

Shifts Produced by Batrachotoxin

The final experimental point concerns the action of another drug, batracho-toxin, that produces sustained increases in G_{Na}. The usual Na currents were measured with the fresh cell; E_{Na} was ~+86 mV. As expected, addition of batrachotoxin (5 × 10⁻⁸ g/ml) produced a slowing of Na inactivation (Khodorov et al., 1975; Bartels-Bernal et al., 1975, 1977). This effect gradually became more pronounced. After 41 min in batrachotoxin, one of the voltage-clamp trials triggered a sustained depolarization and the resting conductance increased; presumably the batrachotoxin had now inhibited Na inactivation to the point where spontaneous repolarization could not occur. Voltage-clamp trials (Fig. 9, middle) still showed this incomplete activation, but most importantly for the
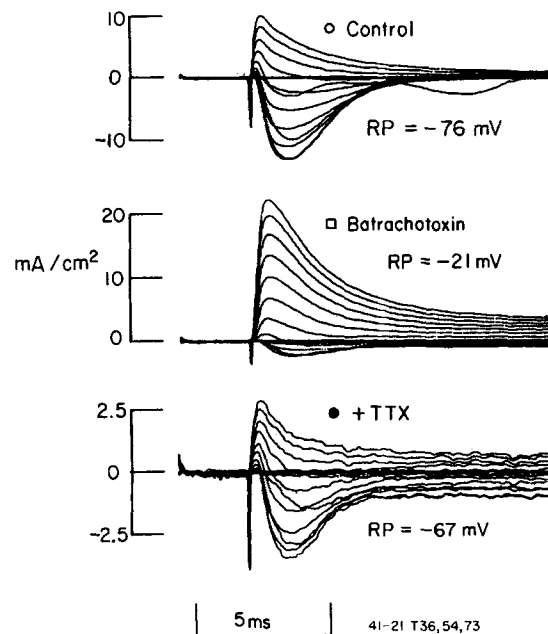

FIGURE 9. Sodium currents before, during, and after exposure to batrachotoxin. Voltage was jumped from −90 mV to a second value; second level ranged from −90 mV to +135 mV in 15 steps of 15 mV. RP, zero-current potential.

present study, such trials also revealed a large reduction of Na ion gradient. E_{Na} was now + 34 mV. Related observations were reported by Bartels-Bernal et al. (1977). Because batrachotoxin's effects are largely irreversible, the ion gradients were reestablished by resorting to tetrodotoxin which independently blocks G_{Na}. Tetrodotoxin was added at a concentration (0.2 μM) sufficient to inactivate most Na channels. The cell repolarized slowly, presumably as the sodium-potassium pump reestablished E_K and E_{Na}. A final voltage-clamp series, 18 min after tetrodotoxin addition, showed that the remaining Na channels still had impaired inactivation kinetics, as expected from earlier studies on batrachotoxin (Khodo-

rov et al., 1975; Bartels-Bernal et al., 1975, 1977). It is important to note that E_{Na} had recovered to +90 mV. Thus batrachotoxin, by increasing G_{Na}, also depletes ion gradients; when the extra conductance is removed, ion gradients can be reestablished.

Nystatin also increases G_{Na} and this drug produced a similar shift in E_{Na}. E_{Na} recovered when nystatin was washed out of the chamber.[1]

DISCUSSION

These observations provide firm support for the suggestion (Karlin, 1967) that sustained permeability increases eventually reduce the transmembrane ion gradients of *Electrophorus* electroplaques. Owing to this effect and to the decrease in agonist-induced conductance with depolarization, the membrane potential does not, as is commonly assumed, measure the short-circuiting of E_t by the agonist-induced conductance. Instead the membrane potential nearly equals the new value of E_t. The Nernst potential shifts vitiate quantitative interpretation of the relation between agonist concentration and membrane depolarization.

On the other hand, conductance measurements do yield a measure directly proportional to the number of open channels (Lester et al., 1975, 1978, Sheridan and Lester, 1975, 1977; Lester et al., 1978). Half-maximal conductances are induced by agonist concentrations at least tenfold higher than those that induce half-maximal depolarizations (Lester et al., 1975, 1978). The higher values provide better estimates of the dissociation constant for the agonist-receptor interaction. Furthermore, conductance measurements have disclosed several phenomena that were masked or distorted in earlier studies on depolarization. These effects include desensitization (Lester et al., 1975) and voltage-sensitivity of the response to agonists (Ruiz-Manresa and Grundfest, 1971; Lester et al., 1975).

It should nonetheless be noted that voltage-clamp results, like those in the present study, can also be distorted by the Na and K activity changes associated with prolonged current flow. In *Electrophorus* electroplaques, these redistributions do not lead to detectable changes in the reversible potential for agonist-induced currents; but they can lead to time-varying leakage currents. As already noted in connection with Fig. 5, the results also indicate that the internal ionic activities affect the ability of acetylcholine receptor channels to pass outward currents.

Ion Fluxes during the Shifts

I have not attempted a full quantitative analysis of the relations among membrane permeability, conductance, and the shifts. The magnitude and time-course of the shifts, however, seem consistent with the known facts about electroplaques. For instance, bath-applied agonist typically induces an extra

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[1] Brodwick, M. S., and H. A. Lester. Unpublished data.

conductance[2] of 10 mmho/cm^2 at the zero-current potential. Assuming that half this conductance is due to Na ions (Lassignal and Martin, 1977) and that the driving force on these ions is >50 mV, Na replaces K at a rate of ~0.25 mA/cm^2 or 2.5 nmol·s^{-1}·cm^{-2}. In agreement with this figure, tracer flux studies show that bath-applied agonist transiently doubles or trebles the resting rate of K efflux, which is of the order of 1 nmol·s^{-1}·cm^{-2} (Whittam and Guinnebault, 1960 a,b; Higman et al., 1964). For an electroplaque with an average thickness of 50 μm the internal Na and K concentrations therefore change at a rate of ~0.5 mM/s. An e-fold diminution of the K gradient would require roughly 100 s, and E_K would change at ~0.2 mV/s, which accounts for the slow drift seen in Fig. 8.

It is difficult to know why the ion changes were not revealed by the atomic absorption measurements of Blumenthal and Changeux (1970) on isolated electroplaques exposed to high agonist concentrations. It must be remembered that isolated electroplaques still retain connective tissue on both faces; in particular the gel covering the non-innervated face is several times thicker than the cell itself. It therefore seems possible that the ion exchanges occur mainly between the nearby connective tissue and the cell interior, with no measureable changes in the preparation as a whole.

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[2] Flux and conductance measurements refer to unit of window area, not of membrane area. See Lester et al. (1978) for a discussion.

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