J. Physiol. (1977), **266**, *pp.* 139–156
With 10 *text-figures*
Printed in Great Britain

RECTIFICATION IN *APLYSIA* STATOCYST RECEPTOR CELLS

BY M. L. WIEDERHOLD

From the Neurobiology Department, Armed Forces Radiobiology Research Institute, Bethesda, Maryland 20014, U.S.A.

(*Received 21 June 1976*)

SUMMARY

1. Membrane slope resistance of *Aplysia* statocyst receptor cells was measured by passing constant current pulses, using a bridge circuit. In response to downward tilt all cells which responded exhibited depolarization but this could be accompanied by either decrease, increase or no measurable change in slope resistance, depending on resting membrane potential.

2. By altering membrane potential with d.c. and measuring slope resistance with constant current pulses, these cells are shown to exhibit both anomalous and delayed rectification. Either hyperpolarization or depolarization from one potential can cause the slope resistance to decrease by as much as a factor of 5.

3. The response to standard tilt can be changed from an increase in slope resistance to a decrease, or vice versa, by altering membrane potential.

4. When membrane potential was held constant during downward tilt, the slope resistance always decreased.

5. Slope resistance, the voltage response to standard tilts and the amplitude of membrane potential fluctuations all vary with average membrane potential in a similar manner.

6. These findings are incorporated into a circuit model in which anomalous and delayed rectification are represented by voltage-controlled elements. The response to tilt is always modelled as introducing a parallel conductance pathway with a large positive reversal potential.

7. The model demonstrates that slope resistance can be increased by adding a parallel shunt pathway if the latter brings the membrane out of the anomalous rectification region.

8. The model also demonstrates how delayed rectification can greatly alter the reversal potential inferred from measurements at potentials below actual reversal.

INTRODUCTION

In the previous paper (Gallin & Wiederhold, 1977), it was concluded that the depolarizing receptor potential of the *Aplysia* statocyst receptor cells is generated by a permeability increase predominantly, if not exclusively, to Na^+ ions. This was manifest by a decreased slope resistance when the preparation is tilted such that the receptor cell under study is lowered to come into contact with the statoconia. Using extrapolation procedures, the equilibrium potential for the conductance increase was previously estimated to be near -20 mV (Wiederhold, 1974).

The effects which the rectifying properties of the receptor cell membrane can have on transduction are reported here. Anomalous rectification, i.e. a decrease in membrane resistance as a cell is hyperpolarized (Freygang & Adrian, 1961; Adrian & Freygang, 1962; Kandel & Tauc, 1966), can cause an apparent resistance *increase* or no change in slope resistance to be associated with the depolarizing receptor potential when, in fact, the receptor potential resulted from a resistance decrease. Delayed rectification, i.e. a decrease in membrane resistance as a cell is depolarized (Hodgkin, Huxley & Katz, 1949), can greatly alter the reversal potential inferred by extrapolation. (The term 'delayed rectification' is used here for convenience. Although the rectification is in the proper direction and a time delay is illustrated, to strictly justify using the term, a predominant selectivity to K^+ would also have to be demonstrated, and this was not tested.)

Data will be presented describing the passive membrane properties of the receptor cells in the resting and physiologically excited states. A simplified model is proposed, incorporating the anomalous and delayed rectification, which predicts several unusual features of the response. These features are verified by modifying the receptor cell membrane potential with injected current.

METHODS

The preparation and recording techniques used here are the same as those described in the preceding paper (Gallin & Wiederhold, 1977). All experiments were performed in Instant Ocean artificial sea water. A number of experiments described here involved passing steady currents (d.c.) through the recording micro-electrode, using an active, calibrated bridge circuit. With the electrode in the bath and the bridge balanced to give no voltage deflexion for 300 msec current pulses, up to ± 2 nA of d.c. could generally be passed with less than 3 mV potential change. In most experiments $< 0{\cdot}5$ nA d.c. was passed and these currents caused no measurable potential change with the electrode in the bath. When necessary, the bridge was rebalanced to have the membrane charging initiate at the base line when d.c. was passed. If bridge unbalance could have significantly affected results when larger d.c. was passed, this is noted in the text (e.g. Fig. 6).

The R.M.S. value of noise voltage was measured with an a.c.-to-d.c. converter (Burr-Brown, 1963) including a capacitor-coupled input to block d.c. current and having a half-power passband from 0·16 Hz to 110 kHz. The converter's output was calibrated with a Ballentine true R.M.S. meter, so that its d.c. output could be referred to a true R.M.S. value of the noise voltage input.

RESULTS

In contrast to the resistance decrease measured with small current pulses illustrated in the previous paper (Gallin & Wiederhold, 1977), a number of cells showed an apparent resistance increase during a depolarizing response to downward tilt. Such a cell is illustrated in Fig. 1. This cell

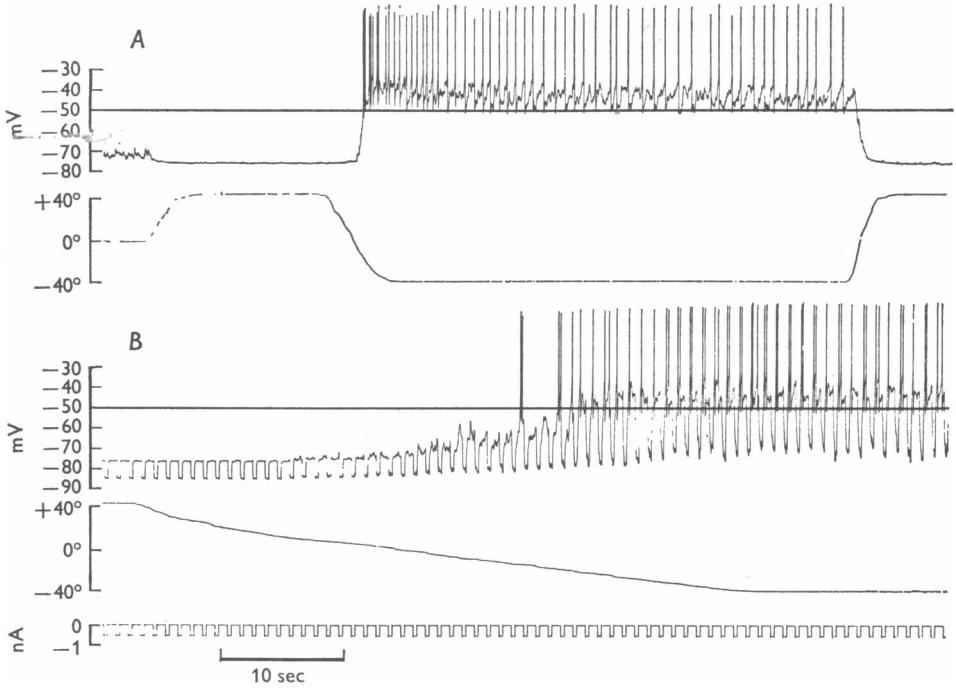

Fig. 1. Membrane potential and resistance changes in response to tilt. *A*, membrane potential response. Upper trace: membrane potential with −50 mV reference line. Lower trace: tilting table position. As cell is tilted from +40° (cell-up position) to −40° (cell-down position) membrane depolarized from −76 to approximately −40 mV. *B*, membrane slope resistance measured with −0·5 nA, 300 msec constant current pulses delivered at 1/sec during slow tilt from +40 to −40°. During tilt membrane depolarized from −75 to approximately −43 mV and slope resistance measured from potential deflexion produced by current pulses increases from 21 to approximately 56 MΩ. First two traces as in part *A*, lower trace: current pulses. Action potential amplitude for this cell: 115 mV peak-to-peak.

had a membrane potential of −76 mV and very small fluctuations in the cell-up position and depolarized by approximately 31 mV when tilted to the cell-down position. However, the 'slope resistance', measured with 0·5 nA hyperpolarizing pulses *increased* from 21 to approximately 56 MΩ during the response. This is all the more significant since there is considerable action potential activity during the response, which might be expected to lower the cell's input resistance.

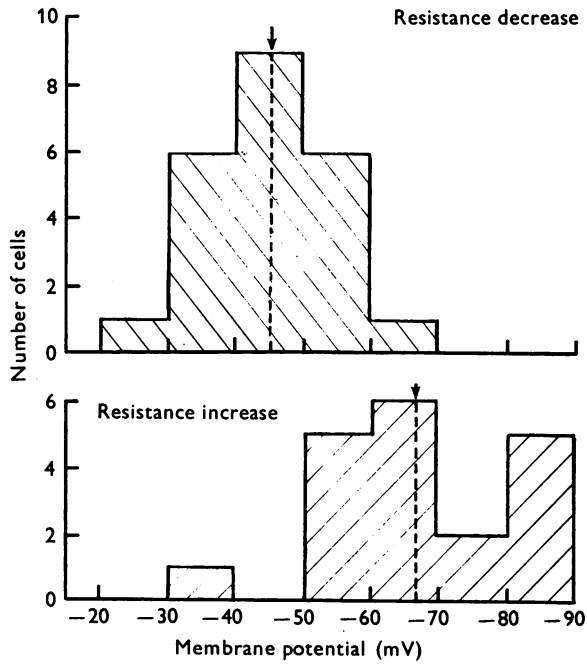

Fig. 2. Distribution of cells observed at different resting potentials. Upper histogram: cells exhibiting measurable decrease in slope resistance as they depolarized in response to a downward tilt. Dashed line and arrow indicate mean resting potential for these cells of −45 mV. Lower histogram: as above for cells exhibiting an increase in slope resistance as they were tilted down. Mean resting potential for these cells is −67 mV.

Nearly as many cells exhibited slope-resistance increase responses as resistance decreases. Those with slope-resistance increases on the average had more negative resting potentials than those showing a slope-resistance decrease. Histograms of frequency-of-observation of cells with different resting membrane potentials for the two types of response are shown in Fig. 2. The mean resting potential for slope-resistance decrease cells was −45 mV, whereas that for slope-resistance increase cells was −67 mV.

In fact, more than 25 % of the slope-resistance increase cells had membrane potentials between −80 and −90 mV. A number of cells with resting membrane potentials between −50 and −60 mV exhibited depolarizing responses to downward tilt, but no measurable change in slope resistance was detected.

The results in Fig. 2 suggest that the membrane potential *per se* might influence the form of the response. Thus, the effects of changing membrane potential on other membrane properties were studied. In Fig. 3*A*, −0·5 nA current pulses were used for measuring membrane resistance while

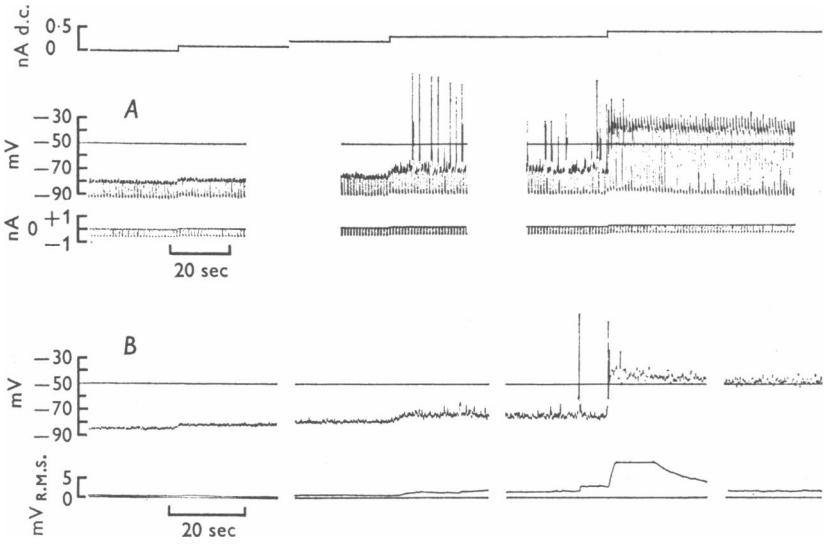

Fig. 3. Effect of membrane potential on slope resistance and potential fluctuations. *A*, −0·5 nA, 300 msec current pulses at 1/sec superimposed on d.c. current varying from 0 to +0·4 nA in 0·1 nA increments (transition from +0·1 to +0·2 nA d.c. omitted). Amount of d.c. indicated schematically across top of Figure, which applies to both parts *A* and *B*. Top trace: membrane potential with −50 mV reference line. Second trace: current applied through micro-electrode. Action potentials: 60 mV peak-to-peak. *B*, membrane potential changes with increasing d.c. as in *A* but no current pulses superimposed. Top trace: membrane potential with −50 mV reference line. Second trace: output of a.c.-to-d.c. converter giving root-mean-square (R.M.S.) amplitude of membrane noise voltage for components from 0·16 Hz to 110 kHz (see Methods). The average membrane potentials at 0 through +0·4 nA d.c. were −84, −82, −79, −74 and −48 mV respectively. The R.M.S. noise voltages at these potentials were 0·32, 0·49, 0·62, 1·38, and 1·70 mV R.M.S. respectively. The a.c.-to-d.c. converter had a settling time of 7·6 sec so that measurements could only be made 20 sec or more after a change in d.c. or the occurrence of an action potential. Sufficient time has been removed from the separate segments of data to allow for complete settling. Note different time scales of *A* and *B*.

membrane potential was altered with steady current (d.c.). It is apparent that as the membrane potential was made more positive, especially at +0·3 and +0·4 nA d.c., the slope resistance (proportional to the voltage change produced by the constant current pulses) increased dramatically. The increment in average membrane potential for successive 0·1 nA increases in the steady current also increases at these levels, as can be seen

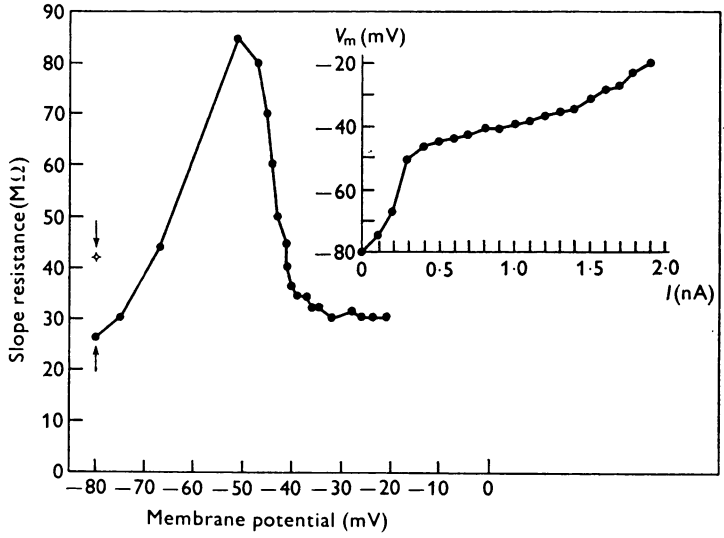

Fig. 4. Slope resistance at different membrane potentials. Slope resistance measured with −0·5 nA, 300 msec constant current pulses superimposed on d.c. ranging from 0 to +1·9 nA as in Fig. 3 (this is a different cell). Upward-pointing arrow indicates measurement at beginning of run. Open circle with downward pointing arrow is measurement with 0 d.c. at end of run, indicating that the slope resistance increased from 26 to 42 MΩ throughout the passage of current. Inset indicates the average membrane potential (between current pulses) at each value of d.c., measured 20–30 sec after changing d.c.

more clearly in Fig. 3*B*. The gradual decline in potential after initiation of the +0·4 nA d.c. resembles the delayed onset in the classical description of 'delayed rectification' (Hodgkin *et al.* 1949). As the membrane potential was increased from −80 mV to −38 mV, the slope-resistance increased from 22 to 98 MΩ.

Fig. 3*B* also illustrates that the amplitude of the membrane potential fluctuations increases as the cell is depolarized and its slope resistance increased. The trace labelled mV R.M.S. shows the root-mean-square amplitude of all components of this noise voltage from 0·16 Hz to 100 (kHz). Since the measuring device has a settling time constant of 7·6 sec, it was

necessary to measure the noise voltage 20 sec or more after a change in current or the occurrence of an action potential. Thus, the R.M.S. amplitude of the noise voltage can be read after the break in the record at each value of steady current (sufficient time has been omitted from the records to allow for complete settling of the instrument).

In Fig. 4 the slope resistance is plotted *vs.* membrane potential for another cell whose resting potential (without applied d.c.) was −80 mV.

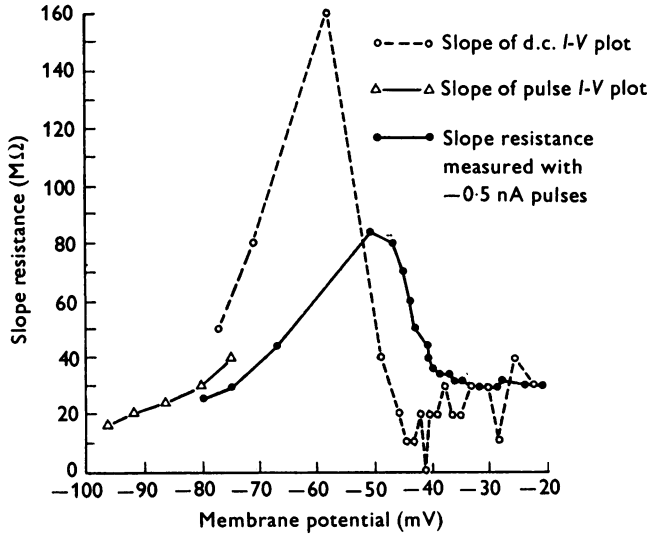

Fig. 5. Comparison of slope resistance measured with −0·5 nA, 300 msec pulses (replotted from Fig. 4; filled circles, continuous line), the slope of the steady-state I–V plot (from Fig. 4; open circles, dashed line) and the slope of an I–V plot measured with 300 msec pulses ranging from +0·2 to −1·0 nA (open triangles, continuous line). Note that where they overlap, the two measures made with pulses are similar, although they differ considerably from the d.c. measure (see text).

Here the resistance measured with −0·5 nA pulses increased from 26 to 85 MΩ as the cell was depolarized to −52 mV. With further depolarization the slope resistance again decreased. Thus, this cell passed rapidly from anomalous rectification (decreasing resistance at more negative potentials) to delayed rectification (used here to denote decreasing resistance at more positive potentials).

The inset in Fig. 4 shows the average membrane potential produced by the steady currents upon which the pulses were superimposed. Although these data qualitatively resemble the change in resistance measured with pulses, the agreement is not quantitative.

This quantitative discrepancy is made more explicit in Fig. 5 where the

slope resistance is replotted along with the slope between succeeding points in both the steady-state I–V plot and that measured with different amplitude current pulses without d.c. The slope of the d.c. I–V plot, centred at −58 mV, is nearly twice the value of slope resistance measured with −0·5 nA pulses at −52 mV. This discrepancy is in all likelihood due to problems inherent in the measurements made with current pulses. Due to the potential fluctuations inherent to these cells, rather large current pulses were needed to produce a reliably measurable potential change. Although the −0·5 nA pulses did not cause extensive voltage excursions at 0 d.c., they certainly did in the regions where the slope resistance was large. In Fig. 3 it can be seen that at 0 d.c. the current pulses only produced an 11 mV potential change, and in this region the membrane is relatively linear. However, at +0·4 nA d.c., the same pulses drove the membrane so far back in the negative direction that at the end of the pulse the membrane was no longer in the high-resistance region. Thus, if small current pulses could have been used, the slope resistance measured between −70 and −40 mV in Figs. 4 and 5 would have been much greater. A further underestimation of slope resistance in the high resistance regions is due to the length of pulse used. In order to follow the time course of resistance changes during tilts, it was necessary to present pulses at a repetition rate of at least one per sec. In order to clearly establish the average potential between pulses, 300 msec pulses were used. Although these pulses allowed for nearly complete membrane charging in the lower resistance regions (e.g. 0 d.c. in Fig. 3), in the high resistance regions where the membrane time constant increased, the charging was not always complete (e.g. Figs. 1, 6*A* and *C*). From direct, on-line observation of the oscilloscope traces the change in time constant was judged to cause an underestimation of slope resistance of not more than 15 %. Thus, the effects of large current pulses and changing time constant can lead to a considerable underestimation of slope resistance and it should be understood in the data presented here that the larger resistances, measured with current pulses, may in fact be underestimated by as much as a factor of two, even though the smaller resistances are accurate. Although these inaccuracies detract from the quantitative aspects of the data, they indicate that the effects of rectification are even greater than illustrated in the Figures and Tables.

In order to control for the possibility that the rectification observed was an artifact of the recording system, several unidentified cells in the pedal and pleural ganglia were studied. For all of these cells the slope resistance increased with steady hyperpolarization. Thus, they did not exhibit anomalous rectification.

That the membrane potential can, indeed, change the nature of the responses is illustrated in Fig. 6. Here constant current pulses were applied

as membrane potential was altered with d.c. Similar tilts were applied at each d.c. level. The average membrane potential and slope resistance in the various states are tabulated in Table 1. With no steady biasing current, this cell has a slight resistance decrease associated with the depolarizing

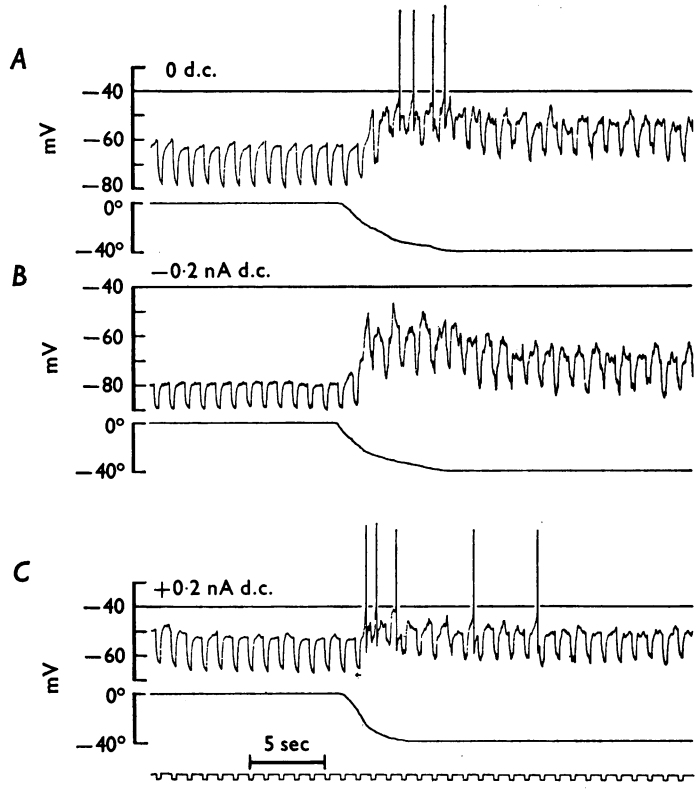

Fig. 6. Effect of membrane potential on slope-resistance change caused by downward tilt. For each part, traces are as in Fig. 1*B*. Current pulses are −0·2 nA, 300 msec, presented one per sec as indicated in the bottom trace, which applies to *A*, *B*, and *C*. *A*, 0 d.c.; *B*, −0·2 nA d.c.; *C*, +0·2 nA d.c. −40 mV reference line for each part. Average potential and resistance with different tilts and currents are given in Table 1.

response to downward tilt. However, when the cell was hyperpolarized with −0·2 nA d.c., the response became a slope-resistance increase and with +0·2 nA d.c. depolarization, a larger resistance decrease than in the control situation was observed. With 0 d.c., a 10 mV depolarization and a 14 % decrease in slope resistance were obtained during the downward tilt. With the hyperpolarizing current there was a 12 mV depolarization and 42 % increase in slope-resistance response, while with depolarization there

was only a 2 mV depolarization but a 20% decrease in slope resistance in response to the tilt. Because of the change in time constant with potential that is evident in Fig. 6 (see above), some of the resistances are probably underestimates. This inaccuracy appears to be greatest in the table-level position with 0 and +0·2 nA d.c. and in the cell-down position with −0·2 nA d.c. Thus, the true percentage change in slope resistance caused by downward tilt with all values of d.c. are also underestimated.

TABLE 1. Effect of membrane potential on response to tilt

	Potential (mV)		Resistance (MΩ)	
D.c. (nA)	Table 0°	Table −40°	Table 0°	Table −40°
0	−62	−52	84	72
−0·2	−79	−67	51	72
+0·2	−52	−50	69	55

TABLE 2. Effect of restoring membrane potential during tilt

	Potential (mV)		Resistance (MΩ)	
D.c. (nA)	Table 0°	Table −40°	Table 0°	Table −40°
0	−83	−70	51	76
−0·3	—	−85	—	46

In other cases where a slope-resistance increase response was observed, if the membrane potential was restored to near its original value with d.c. during the tilt, a slope-resistance decrease was observed. Values of potential and resistance for such a case are given in Table 2. Here, with 0 d.c. there was a 33% increase in slope resistance during downward tilt, but when the membrane potential was brought back close to that in the table-level, 0 d.c. state, the slope resistance is seen to be 10% less than at that potential before tilting. When the membrane potential was held between −83 and −84 mV by injected current, the membrane potential fluctuations were larger in the cell-down position than with the table level. Although R.M.S. amplitude of the noise voltage was not measured in this experiment, the amplitude of the fluctuations in the cell-down position at −85 mV (−0·3 nA d.c.) was 2–3 times greater than with the table level at −83 mV (0 d.c.).

The usual procedure for determining the reversal potential of either synaptic or sensory potentials is to vary the membrane potential with injected current and observe changes in response amplitude. The variation of the amplitude of responses to similar tilts over a wide range of membrane potentials is illustrated in Fig. 7. This cell's resting potential without

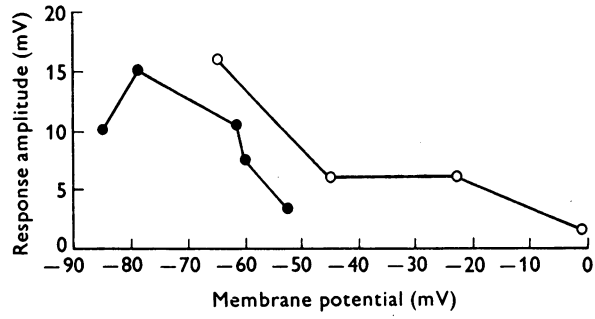

Fig. 7. Effect of membrane potential on responses to similar tilts. Membrane potential altered by passing d.c. from 0 to approximately +4 nA. Each point represents the depolarization produced by a tilt from 0° (table level) to −40° (cell-down) similar to those of Fig. 6, without current pulses presented. Filled and open circles represent separate runs on the same cell. With 0 d.c., resting membrane potential was −62 to −65 mV. Same cell as Fig. 6.

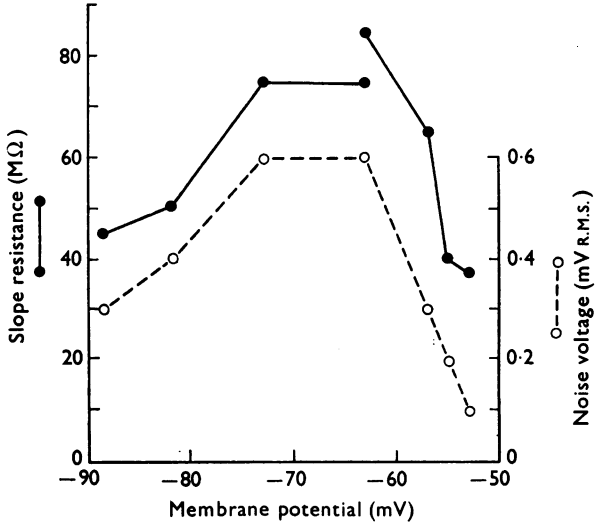

Fig. 8. Dependence of slope resistance (filled circles) and noise voltage (open circles) on membrane potential. Slope resistance measured as in Fig. 6 and R.M.S. amplitude of noise voltage (membrane potential fluctuations) measured as in Fig. 3*B*. Same cell as Fig. 6.

d.c. varied from −62 to −65 mV. The data points represented by different symbols correspond to two successive runs. Note that at membrane potentials more negative than −80 mV the response begins to decline, and that with the membrane depolarized to near 0 mV, the response did not reverse. This last potential can only be taken as approximate since such large d.c. currents had to be passed (~ +4 nA) that we cannot be confident that the bridge was still balanced. For this reason no attempt was made to pass larger currents. However, it should also be noted that the change in response amplitude with changing membrane potential is more gradual at potentials above −45 mV than below this level.

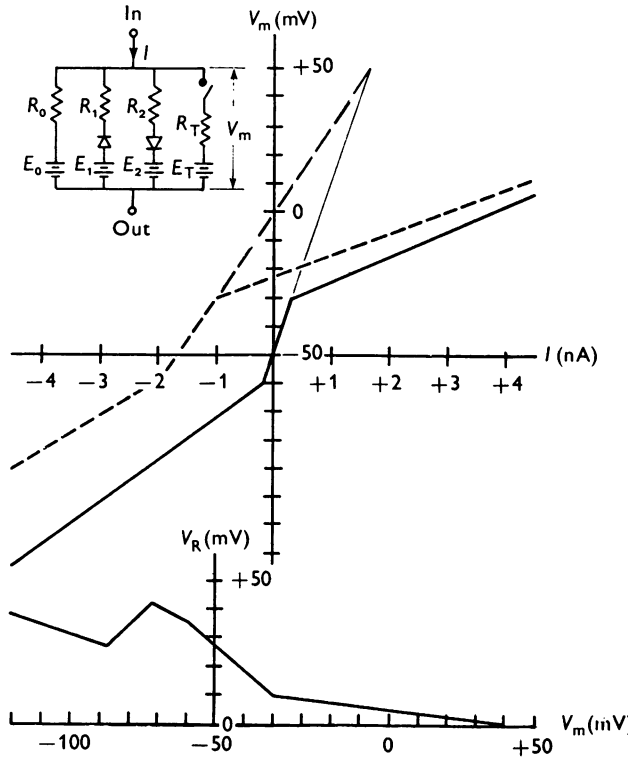

Fig. 9. For legend see facing page.

The amplitude of potential fluctuations also varied with average potential. Slope resistance and the R.M.S. amplitude of the noise voltage are plotted *vs.* membrane potential in Fig. 8 for the same cell as is illustrated in Figs. 6 and 7. Note that the two parameters vary in nearly the same form with membrane potential. By comparing these results with those at comparable potentials in Fig. 7, it can also be seen that the noise voltage

amplitude varies with membrane potential in nearly the same manner as does the response amplitude for similar tilts.

DISCUSSION

The experimental results presented in this and the preceding paper can be understood, at least qualitatively, in terms of the simplified circuit model shown in Fig. 9. R_0 and E_0 represent the membrane resistance and potential in the resting state with no current or tilt applied. Typical values of 60 MΩ and −50 mV, respectively, have been assumed. R_1 and E_1 represent the anomalous rectification which, for simplicity, is here assumed to be strictly potential-controlled, a resistance of 20 MΩ being introduced in parallel to the 60 MΩ resting resistance at potentials below −60 mV. Thus, without a tilting stimulus, at potentials less than −60 mV the total slope resistance will be 15 MΩ. Similarly, delayed rectification is modelled as a parallel resistance of 10 MΩ brought in at potentials above −30 mV.

Fig. 9. Equivalent circuit model of statocyst receptor cell membrane incorporating anomalous and delayed rectification. 'In' and 'out' refer to inside and outside the cell membrane, I to membrane current and V_m, membrane potential. The branch containing resistance R_0 and battery E_0 represents the resting membrane between the anomalous and delayed rectifying regions. The branch with R_1, E_1 and the inward-conducting diode represents anomalous rectification which is modelled as an additional resistance (R_1) which can conduct current only at membrane potentials more negative than E_1. The branch with R_2, E_2 and the outward-conducting diode represents delayed rectification similarly modelled as a parallel channel which only conducts at membrane potentials more positive than E_2. The branch containing R_T, E_T and a switch represents the transduction mechanism which is activated (i.e. the switch is closed) when a cell is lowered to have its cilia in contact with the statoconia. The values assumed for the various components are: $R_0 = 60$ MΩ, $E_0 = -50$ mV, $R_1 = 20$ MΩ, $E_1 = -60$ mV, $R_2 = 10$ MΩ, $E_2 = -30$ mV, $R_T = 60$ MΩ, $E_T = +50$ mV. In the membrane potential (V_m) – current (I) plot for this model the continuous line corresponds to the cell-up position with the switch open and the dashed line represents the stimulated, cell-down position with the switch closed. The fine continuous and dashed lines indicate that within any region of rectification the extrapolated reversal potential of the response to tilting is +50 mV. Slope resistance measured with small current pulses, as in Figs. 1, 3 and 6, corresponds to the slope of such voltage–current relationships. Bottom portion of Figure is plot of membrane potential response amplitude (V_R) for a constant tilt, represented in the model by closing the switch, at different membrane potentials (V_m). This corresponds to the distance between the two V_m–I characteristics at different fixed currents. The response would reverse its sign at potentials more positive than +50 mV.

This parallel combination has a total slope resistance of 8·6 MΩ. Marmor (1971) has studied rectification in the *Anisodoris G* cell and concludes that the potentials at which anomalous and delayed rectification become apparent are very similar in all *G* cells, even those with quite different total resistances or different resting potentials. This finding lends support to modelling both types of rectification by voltage-controlled elements. Although both types of rectification have been modelled with diodes and batteries, these batteries should not be confused with ionic equilibrium potentials. E_1 and E_2 in the model are used purely empirically to allow R_1 and R_2 to conduct only at potentials below E_1 and above E_2, respectively. Since the predominant permeability change during the response was concluded to be to sodium ions (Gallin & Wiederhold, 1977), the transduction channel, represented by R_T and E_T, was assumed to have a reversal potential (E_T) of +50 mV. R_T was chosen equal to R_0 since in several cases the slope-resistance decrease during tilt was as much as 50 %. In the current–voltage plots of Fig. 9 the continuous line represents a receptor in the cell-up position, i.e. without the transducing channel activated, whereas the dashed line represents the stimulated receptor, with the switch closed. Since this is a piecewise-linear model with discrete changes in slope resistance and since the potentials at which anomalous and delayed rectification become evident varied from one cell to another, the model cannot be expected to correspond in detail with all of the experimental data; but as will be shown, the qualitative agreement is instructive.

In the lower portion of Fig. 9 the membrane potential responses of the model to the same tilt at membrane potentials from −120 to +50 mV are shown. The response has a maximum at −72·5 mV and decreases with hyperpolarization to −87·5 mV. It decreases with depolarization from −72·5 to −30 mV and then decreases more gradually with depolarization up to +50 mV; it would reverse only above this potential. These features are similar to the data shown in Fig. 7.

As shown in Fig. 10*A*, at any constant potential the slope resistance of the model is lower in the tilted (stimulated) state, although the percentage decrease is largest between −60 and −30 mV. This corresponds to the data of Table 2 wherein, if the cell was allowed to depolarize during a downward tilt the slope resistance increased but when the potential was held near −83 mV the underlying slope-resistance decrease became apparent.

Fig. 10*B* demonstrates that when membrane current is controlled, rather than potential, there is a region (labelled II) in which the slope resistance increases during a stimulating tilt. The depolarizing response, although caused by the addition of a parallel resistance or shunt path, brings the cell out of the anomalously rectifying region and this increased

membrane resistance is greater than the decrease caused by the transducer channel. This feature of the model is consistent with the data of Fig. 6. In this case the 0 d.c. condition corresponds to region III in Fig. 10*B*. Passing a steady hyperpolarizing current (Fig. 6*B*) brings the cell into region II where tilting causes a net increase in slope resistance. Passing a

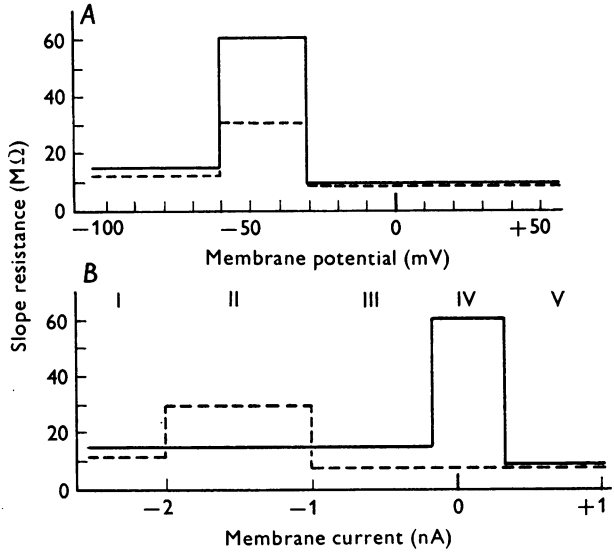

Fig. 10. Dependence of slope resistance on membrane potential and membrane current predicted from the model of Fig. 9. For both portions continuous line corresponds to cell-up position with the switch open and dashed line to cell-down position with the switch closed. *A*, slope resistance in two positions if membrane potential is held constant. Note that slope resistance is reduced by closing the switch at all potentials although the fractional change is greatest at potentials between −60 and −30 mV. *B*, slope resistance in two positions if membrane current is controlled. Roman numerals above plots indicate regions discussed in the text. Note that for currents between −1 and −2 nA, closing the switch increases slope resistance.

steady depolarizing current (Fig. 6*C*) brings the cell into a state analogous to region IV in which the decrease in slope resistance during tilt is greater than in region III. The change in response amplitude at different potentials also agrees with the predictions of the model (lower portion of Fig. 9). The amounts of current applied in Fig. 6 do not correspond to those in regions II, III, and IV of Fig. 10*B* but this can be ascribed to the fact that this cell was already in the anomalously rectifying region with no steady current applied. A more complete model, rather than the piecewise-linear simplification assumed here, would show gradual transitions between the

various regions of Fig. 10 and could be made to fit the experimental data more quantitatively. However this would require adjusting a continuum of parameters to the properties of each cell. The aim here was rather to develop a more general model from which the nature of potential and resistance changes caused by physiologic stimulii, with a receptor cell in a variety of states, could be understood in terms of familiar mechanisms.

This analysis illustrates that rectification can greatly affect the interpretation of differences in membrane resistance measured with constant current pulses. In fact, an apparent resistance increase can be brought about by adding an additional conductance path in parallel to those existing. For cells whose resting membrane potential is above the region of anomalous rectification, the decrease in slope resistance associated with the depolarizing response to tilt could be enhanced by entering the region of delayed rectification. Thus, it would be possible to generate a large depolarizing response with an underlying change in resistance of the transduction mechanism much smaller than that indicated by the change in slope resistance. The observations that, when potential is controlled, the response to tilt is always a resistance decrease (Table 2) and that the ionic basis of the response is predominantly Na^+ (Gallin & Wiederhold, 1977), indicating a large positive reversal potential, confirm that the underlying mechanism of transduction is a decrease in membrane resistance produced directly by the mechanical stimulus.

If the response amplitude were studied only over a restricted range of potentials, such as -80 to -30 mV in the data of Fig. 7, or the behaviour of the model (Fig. 9) between -60 and -30 mV, a reversal potential of between -20 and -40 mV would be predicted (Wiederhold, 1974). The model, including delayed rectification, makes these data compatible with the ion-substitution experiments (Gallin & Wiederhold, 1977) indicating a reversal potential near $+50$ mV. Delayed rectification has here altered the extrapolated reversal potential by 70 mV. The effects of such rectification on the reversal potential of synaptic potentials has been treated graphically by Ginsborg (1967) and analytically by Burke & Ginsborg (1956) and Jack, Noble & Tsien (1975). Detwiler & Fuortes (1975), in the *Hermissenda* statocyst, have noted an apparent difference in the reversal potential for responses to large and small impulsive stimuli. The fact that rectification can so greatly affect the extrapolated reversal potential, depending upon what membrane potential range the response enters, suggests that delayed rectification, which is apparent in their data, could influence such conclusions.

The data of Fig. 2 would indicate that in these cells anomalous rectification usually becomes apparent at membrane potentials below -50 to -60 mV. The one cell with a membrane potential of -38 mV, which

showed a slope-resistance increase during its depolarizing response to tilt, was unusual in that anomalous rectification was noted at potentials below −30 mV. One finding which we do not understand is that so many cells had such large negative resting potentials, ranging down to −90 and occasionally even −100 mV. This is much greater than is usually seen in *Aplysia* neurones and our own recording from neurones in the pedal, pleural and cerebral ganglia did not reveal resting potentials below −60 mV.

The fact that the fluctuations in potential vary with the membrane potential in a manner similar to slope resistance (Fig. 8) can influence the interpretation of the fluctuations which was offered in the preceding paper (Gallin & Wiederhold, 1977). Since in those cases where the fluctuations are absent in the cell-up position, the membrane potential was also more negative, the reduction might be due simply to the decreased slope resistance. This cannot be the complete explanation, since in cases such as Fig. 3 of the preceding paper (Gallin & Wiederhold, 1977), the fluctuations did increase during the downward tilt when the slope resistance decreased. Also, for the cell described in Table 2, when membrane potential was held nearly constant, the amplitude of the fluctuations clearly increased with downward tilt (see Results, p. 148). Thus, it appears that the fluctuations are increased by increasing contact of cilia with statoconia, although the amount of change in fluctuations with tilt will be affected by concomitant changes in membrane resistance.

Anomalous rectification has been described in one other sensory cell (Werblin, 1975). Although the data of Adrian & Slayman (1966) demonstrate that anomalous rectification can limit the degree to which an electrogenic sodium pump will hyperpolarize a cell, no physiological advantage of such rectification in sensory coding has been suggested. Detwiler & Alkon (1973) have described extensive inhibitory synaptic input to the statocyst of *Hermissenda*. Anomalous rectification would increase the effectiveness of hyperpolarizing synapses in blocking action potentials. If, in the model of Fig. 9, there were no anomalous rectification, the membrane-potential response to physiologic stimuli would increase in proportion to hyperpolarization. The *Aplysia* statocyst cells show considerable adaptation to both physiologic (Figs. 3 and 5 of Gallin & Wiederhold, 1977) and electric (Fig. 3, this paper) stimulation, action potentials being evoked at much lower membrane potentials by increasing, rather than steady, stimuli. Thus, if there were no anomalous rectification, when a cell was hyperpolarized by synapses remote from the cell body, small sudden stimuli might still be able to elicit action potentials. However, with anomalous rectification present, when a cell is hyperpolarized, it is effectively 'turned off'. This suggestion complements that of Kandel & Tauc

(1966) that in cells with only excitatory synaptic input, anomalous rectification increases the efficacy of repeated synaptic excitation since the latter will depolarize the cell sufficiently to bring it out of the rectifying region and allow greater summation of synaptic potentials.

I thank Drs M. G. F. Fuortes, T. G. Smith, F. Conti, L. Cervetto, D. R. Livengood, E. K. Gallin and D. O. Carpenter for helpful discussions and criticism of the manuscript and Mr G. A. Hopp for technical assistance.

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