The Action Potential in the Smooth Muscle of the Guinea Pig Taenia Coli and Ureter Studied by the Double Sucrose-Gap Method

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ABSTRACT   The configuration of the electrotonic potential and the action potential observed by the double sucrose-gap method was similar to that observed with a microelectrode inserted into a cell in the center pool between the gaps. In the taenia and the ureter, the evoked spike was larger in low Na or in Na-free (sucrose substitute) solution than in normal solution. However, the plateau component in the ureter was suppressed in the absence of Na. In Ca-free solution containing Mg (3–5 mM) and Na (137 mM), the membrane potential and membrane resistance were normal, but no spike could be elicited in both the taenia and ureter. Replacement of Ca with Sr did not affect the spike in the taenia, nor the spike component of the ureter but prolonged the plateau component. The prolonged plateau disappeared on removal of Na, while repetitive spikes could still be evoked. It was concluded that the spike activity in the taenia and in the ureter of the guinea pig is due to Ca entry, that the plateau component in the ureter is due to an increase in the Na conductance of the membrane, and that both mechanisms, for the spike and for the plateau, are separately controlled by Ca bound in the membrane.

INTRODUCTION

Previous observations on the effects of changing the external Na concentration on the spontaneous spike activity, led to the conclusion that the action potential in the guinea pig taenia coli was due to Na entry, though the sodium carrier system might be rather limited, but that, in the absence of Na, Ca could carry the inward current (Holman, 1957, 1958; Bülbring and Kuriyama, 1963).

More recently, the effects of Na and Ca deficiency have been investigated on the action potential evoked by electrical stimulation. The results indicate that the contribution of Ca to the action potential is more important than the contribution of Na (Brading, Bülbring, and Tomita, 1969 b).

Several observations on mammalian smooth muscle resemble those made on crustacean muscle whose spike is due to Ca entry (Fatt and Ginsborg,

1958; Hagiwara and Naka, 1964; Hagiwara and Nakajima, 1966; Ozeki, Freeman, and Grundfest, 1966; Takeda, 1967). For example, the action potential is resistant to tetrodotoxin (taenia, Kuriyama, Osa, and Toida, 1966; Nonomura, Hotta, and Ohashi, 1966; Bülbring and Tomita, 1967; ureter, Washizu, 1966; Kuriyama, Osa, and Toida, 1967 a); spike activity is maintained when Ca in external solution is replaced by Ba (taenia, Hotta and Tsukui, 1968; Bülbring and Tomita, 1968, 1969 b); while Mn suppresses spontaneous spike generation and, in higher concentration, also blocks the evoked spike (taenia, Nonomura et al., 1966; Brading et al., 1969 b; Bülbring and Tomita, 1969 b; ureter, Kuriyama et al., 1967 a).

The aim of the present experiments was to analyze the spike mechanism in the taenia coli further by using the double sucrose-gap method. At the same time, the action potential in the guinea pig ureter has been compared with that in the taenia.

In the present study, the double sucrose-gap method was employed in investigating active properties of the membrane in smooth muscles. The double sucrose-gap method would seem to be applicable to the taenia coli and ureter of the guinea pig because they have cable-like properties. However, in the taenia the electrotonic potential observed by this method has a much slower time course than that expected from a time constant of 100 msec obtained by a different method, i.e. when the whole taenia is exposed to hypertonic Krebs solution and responses to external polarization, applied longitudinally to the tissue, are recorded intracellularly (Tomita, 1966; Abe and Tomita, 1968). Therefore, the response obtained by the double sucrose-gap method was first analyzed in order to justify the application of the method to the study of the active properties of the smooth muscles. For this purpose, intracellular recording and sucrose-gap recording were employed simultaneously. Since observations on the mechanical response will be reported in a separate paper, descriptions are confined mainly to the electrical response.

METHODS

The method used was essentially the same as that described by Bülbring and Tomita (1969 a). Of the total muscle length (30–40 mm), a part less than 2 mm in the middle was exposed to test solution, while both ends were bathed in sucrose solution. Krebs solution and Locke solution were used as normal media (Table I). As a substitute for NaCl, sucrose or tris (hydroxymethyl) aminomethane chloride was used. For Na-free solution, $NaHCO_3$ was also omitted and partly replaced with $KHCO_3$, Tris-Cl being used as buffer (pH, 7.2–7.5). The solution used for perfusion of the sucrose-gap contained sucrose 115 g/liter (335 mM). The tissue swelled in this solution probably due to the lack of Ca, as reported by Brading and Tomita (1968). Most of the experiments were usually carried out at room temperature (22–26°C) in order to suppress spontaneous activity, which occasionally occurred at temperatures higher

than 30°C. All parts of the tissue including the sucrose-gaps were kept at the same temperature.

Current pulses (usually 3 sec duration, and 0.1 cycle/sec frequency) were applied across the right sucrose-gap through a series resistance (50 MΩ) from the isolation unit of the stimulator as shown in Fig. 1. The current (I) was measured across a 100 KΩ-resistor inserted between ground and the current source. In some experiments, the voltage (V_2) produced across the right sucrose-gap in response to square current pulses was also measured. The voltage (V_1), produced across the cell membrane of the tissue in the center pool, was measured across the left sucrose-gap. Voltages and current were displayed on a 3 or 4 beam oscilloscope together with

TABLE I
IONIC COMPOSITION

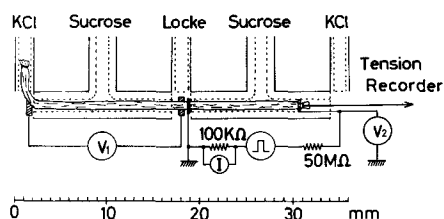| Solution	NaCl	KCl	CaCl₂	NaHCO₃	MgCl₂	NaH₂PO₄	Glucose
	mM	mM	mM	mM	mM	mM	mM
Locke	154.0	5.6	2.2	1.8	—	—	5.6
Krebs	120.4	5.9	2.5	15.5	1.2	1.2	11.5

FIGURE 1. Schematic diagram of the double sucrose-gap method. Current pulses were applied across the right gap through a 50 MΩ resistor and monitored by a 100 KΩ resistor (I). The voltage produced across the left gap (V_1) and that across the right gap (V_2) were measured by cathode follower amplifiers. The dimension of the gap is shown at the bottom.

tension, and recorded on film. An inkwriting oscillograph was also used for continuous recordings of the electrical and mechanical responses.

Ag-AgCl electrodes were used for stimulating and also for recording. The base line of the recorded potential was rather stable when the flow rate of the solutions was kept constant. Since the potential change across the gap was not only due to the membrane potential but also to liquid junction potentials, the change in the membrane potential was difficult to measure accurately when the ionic compositions of the test solutions were changed. In the present experiments, the change in the membrane potential was not studied carefully.

When a microelectrode was inserted into a cell in the center pool which was usually 2 mm long, the electrode for the external recording was used as an indifferent electrode. Tension was recorded by a strain gauge transducer.

RESULTS

A Progressive Change in the Response   After the tissue was set up in the apparatus, there was a gradual change in the responses. Fig. 2 shows an example of such a change in the taenia. Current pulses of a constant intensity were applied throughout. At the beginning of the experiment, the time constant (the time to reach 63% of the steady state) was usually between 100 and 200 msec. Then the time course of the electrotonic potential became slower and its amplitude larger. When a steady state had been reached, the time to reach 63% of the steady state was between 0.5 and 1.5 sec in different preparations. Although it was very roughly exponential, it was not expressed either by an exponential or by an error function when carefully analyzed.
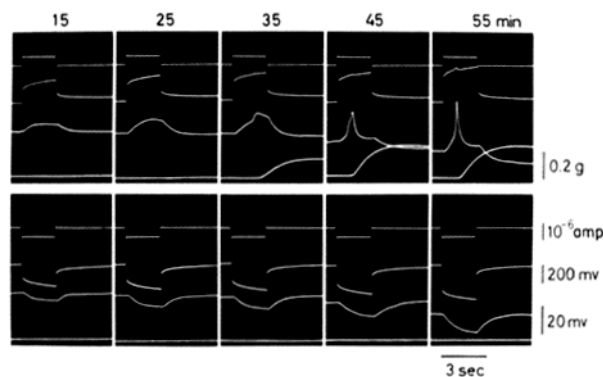

FIGURE 2. Progressive change of the responses 15–55 min after the beginning of the experiment. Taenia coli. 23°C. Tracing from top to bottom, current intensity, voltage across right gap, voltage across left gap, and tension.

The spike usually became larger and sharper. The contraction also increased with time. The voltage produced longitudinally across the right sucrose-gap had two components, a transient step and a slow change. The transient step gradually increased, but the slow component remained roughly the same. This increase of the voltage across the sucrose gap was probably due to an increase in the longitudinal tissue impedance, as observed by Tomita (1969) when the tissue was immersed in pure sucrose solution. The rate of all changes depended on the rate of flow of the sucrose solution, the change being quicker with faster flow of the solution. It usually took 30–60 min before the steady state was reached.

Changes similar to those in the taenia were observed in the ureter. The time course of the electrotonic potential was more or less the same as that of the taenia. In the ureter the spike had a plateau and spike components, as previously observed by intracellular microelectrodes (Bennett, Burnstock, Holman, and Walker, 1962; Irisawa and Kobayashi, 1962; Washizu, 1966;

Kuriyama et al., 1967 *a*) and by the single sucrose-gap method (Cuthbert, 1965; Bennett and Burnstock, 1966). When the whole ureter was used, without opening the lumen of the tissue by a longitudinal incision, jumps in the electrotonic potential often appeared at on and off of current pulses 2–3 hr after the beginning of the experiment.

Comparison of Intracellular and External Recordings Fig. 3 shows responses obtained from the taenia by external recording with the sucrose-gap method and simultaneously by intracellular recording. A microelectrode was inserted into a cell in the middle part of the center pool. The electrotonic potential recorded intracellularly had a larger (about 50%) amplitude and a faster time course than that recorded externally. The time to reach 63% of the steady level of the electrotonic potentials recorded intracellularly was between 0.3 and 1.0 sec in different preparations and was about 30% faster than that recorded with the sucrose-gap method.
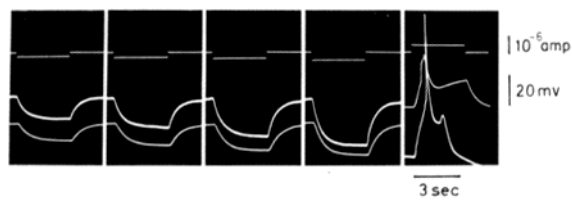

FIGURE 3. Simultaneous recordings across the sucrose-gap and with an intracellular microelectrode. Taenia coli. 25°C. Top, current intensity; middle, intracellular recording (external recording in right end record); bottom, external recording (intracellular recording in right end record). See text for further description.

The difference between the spikes obtained with the two different recording methods was much greater than that between the electrotonic potentials. The externally recorded spikes sometimes had notches on the rising or falling phases. The intracellularly recorded spike had a much larger amplitude (more than twice) and much shorter duration. Its amplitude was often more than 80 mv. This was larger than any value previously reported in 'the taenia (62–63 mv) (Bülbring and Kuriyama, 1963; Kuriyama, Osa, and Toida, 1967 *b*), and is probably due to hyperpolarization of the membrane caused by immersion in sucrose solution as observed in the lobster giant axon (Julian, Moore, and Goldman, 1962).

In the ureter, the differences between the intracellular and external recordings were essentially similar to those in the taenia. However, the differences in spike shape were less marked.

Spatial Decay within the Center Pool One of the reasons for the difference between the intracellular and external recordings could be that the electrotonic potential decayed along the tissue according to cable-like properties

and became small and slow at the junction between sucrose and Locke solutions at the recording side of the center pool. However, since the length of the center pool was 2 mm, and the tissue exposed to Locke solution would be less than 2 mm (probably only 1–1.5 mm) due to sucrose solutions flowing at both sides, the spatial decay is probably not serious. In the experiment shown in Fig. 4, the center pool was lengthened to 5 mm, in order to demonstrate the decay clearly, and a microelectrode was inserted into the ureter at two different places, first near the stimulating gap (upper row) and then near the recording gap (lower row) at a distance of about 4 mm from the first penetration. The sucrose-gap recording showed very small electrotonic potential, probably due to the wide space of the center pool, but a reasonable amplitude of the spike. In the intracellular recording, there was a
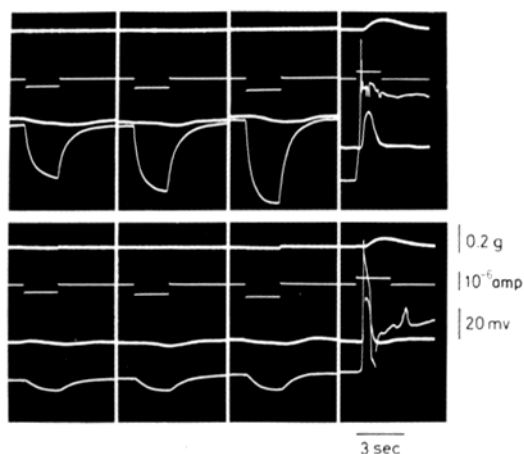

FIGURE 4. Spatial decay determined by intracellular recordings at two different distances from the stimulating site. Ureter. 25°C. Top record, 0.5 mm; bottom record, 4.5 mm from the stimulating gap. Tracings from top to bottom, tension, current intensity, external recording, and intracellular recording.

large decay of the amplitude of the electrotonic potential (to about one-fourth) at a distance of 4 mm. The magnitude of the decay was in good agreement with the values expected from the space constant of 2.5–3.0 mm reported by Kuriyama et al. (1967 a). The time course was much slower at the point far from the stimulating site. The spike amplitude and its rate of rise were more or less the same at both recording sites.

Effects of Sucrose Solution   Since both sides of the tissue in the center pool were immersed in sucrose solution, it was important to study the effects of sucrose solution. However, when Locke solution was completely replaced with sucrose solution, the stimulating artefact increased due to a high electrical resistance of the solution. Therefore, Locke solution was diluted to one-half and to one-tenth with pure sucrose solution. Fig. 5 shows the effects on the taenia of the solution containing one-tenth Locke solution and nine-tenths sucrose solution. The amplitude of the electrotonic potential was increased about three times and the spike usually was also increased. The contraction became

small and slow. The effects appeared gradually as seen from the difference between the records taken 20 and 30 min after the solution was changed, although the rate of change was slightly accelerated by increasing the rate of flow. These changes were reversible. The time course of the electrotonic potential usually changed only slightly. A similar change was observed also in the ureter as shown in Fig. 6.
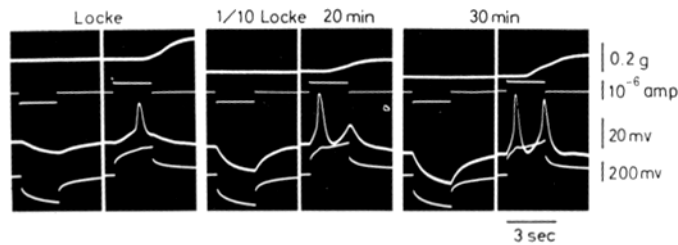

Figure 5.   Effects of dilution of Locke solution with sucrose (one-tenth Locke, nine-tenths sucrose solution). Taenia coli. From top, tension, current intensity, voltage at left gap, and voltage at right gap. Note increase in amplitude of the electrotonic potential 20 and 30 min after the dilution.
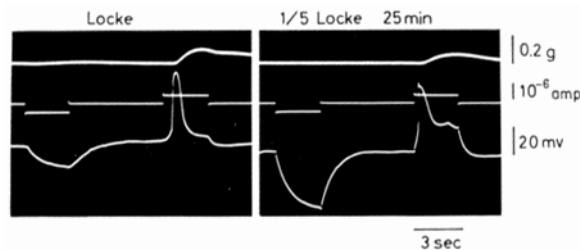

Figure 6.   Effects of dilution of Locke solution with sucrose (one-fifth Locke, four-fifths sucrose solution) on the ureter. Top, tension; middle, current intensity; bottom, potential recording. Note an increase in amplitude of the electrotonic potential after dilution.

Effects of Temperature   The electrotonic potential of the taenia and the ureter had a smaller amplitude and faster time course at a high temperature than at a low temperature as observed in the taenia by Brading, Bülbring, and Tomita (1969 *a*). At 35 °C, the amplitude of the electrotonic potential was 30–50% smaller and the time to reach 63% of the steady level was 60–70% faster than at 25 °C.

Spike Activity in Low Na and Na-Free Solutions

taenia   When the NaCl in Krebs or Locke solution was replaced with sucrose or Tris, leaving only the Na contained in the buffer (16 mM in Krebs, 2 mM in Locke solution), the threshold usually increased, but a spike could

always be evoked, as shown in Fig. 7. These results are in good agreement
with the observations previously made with both intracellular microelec-
trodes and with the double sucrose-gap method (Brading et al., 1969 b;
Bülbring and Tomita, 1969 a). The increase in threshold was larger with
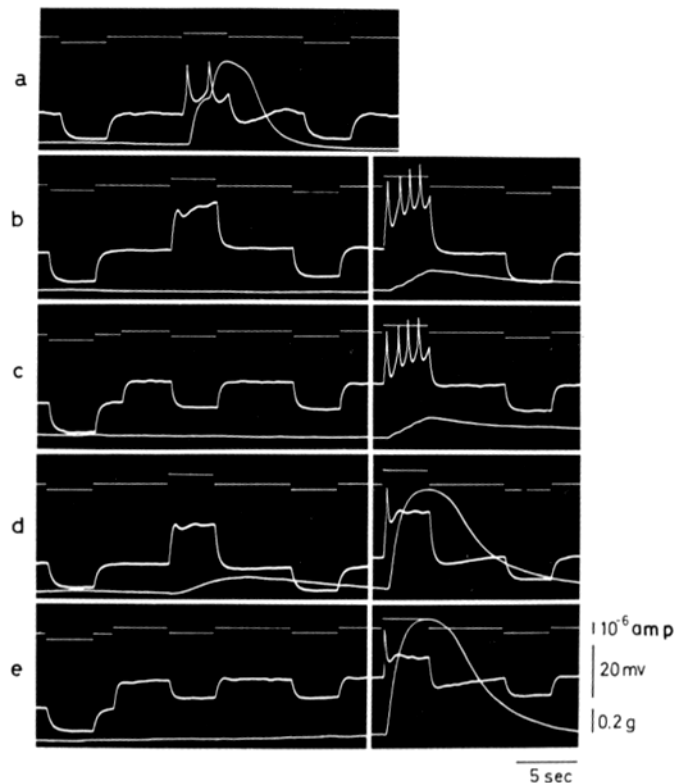Tris than with sucrose substitution. In general, the spike was larger in low

FIGURE 7.   Effects of low Na. Taenia. 32°C. Upper trace, stimulating current; middle
trace, electrical response; lower trace, tension. (a) Control in normal Krebs solution;
(b) 30 min after substitution of sucrose for NaCl (16 mM Na), effect of increasing current
intensity; (c) effect of conditioning depolarization; (d) 30 min after substituting Tris for
NaCl (16 mM Na), effect of increasing current intensity; (e) effect of conditioning de-
polarization. Between the exposures to sucrose and Tris solution complete recovery was
observed in normal Krebs solution.

Na solutions than in the presence of a normal Na concentration. However,
in Tris solution, the spike was sometimes smaller than in normal solution and
in many preparations only a single spike was produced even by a long current
pulse (Fig. 7). The spike activity was the same in a solution containing low
concentrations of Na and in a completely Na-free solution. Some deteriora-
tion in the spike was sometimes observed after 1 hr in low Na or Na-free
solution. When sucrose was substituted for NaCl, the contraction became
small and slow and often a gradual increase in the resting tension was ob-

served. However, when Tris-Cl was used as a substitute for NaCl, the contraction was nearly the same as that of the control, or even greater. Large contractions in Tris-Cl shown in Fig. 7 were partly due to a progressive increase in tension in the course of the experiment, as mentioned earlier.

URETER   The amplitude and number of spikes appearing on a plateau varied in different preparations. The duration of the plateau varied from less than 1 sec to 3 sec. When the duration of the stimulating current pulse was more than 3 sec, a second action potential was sometimes evoked (see Figs. 11 and 13).

When the Na concentration was reduced (2–16 mM Na), the plateau became smaller and the spike larger than in normal solution (Fig. 8). The same
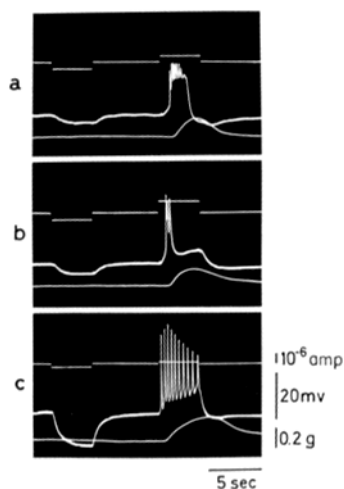

Figure 8. Effects of low Na. Ureter. 24°C. (a) Control in normal Krebs solution; (b) 20 min in Tris solution (16 mM Na); (c) 20 min in sucrose solution (16 mM Na). Between (b) and (c) complete recovery in normal Krebs solution was observed.

change in the action potential was observed in Na-free solution. This change occurred gradually, 30 min after removal of Na from the external solution, the spike amplitude was larger than after 15 min. The tendency towards repetitive activity was less in Tris than in sucrose solution (Fig. 8).

Sometimes, when NaCl was replaced with sucrose, spontaneous activity or anode-break excitation occurred. In some preparations, this activity ceased after about 10 min but in others it lasted for more than 30 min. It may be that these preparations which developed spontaneous activity or break excitation in sucrose solution had a relatively high Cl permeability so that the membrane was depolarized by the reduction of the external Cl. This possibility was supported by the observation that the similar pattern of changes was produced when Cl was replaced with a large anion, benzenesulfonate.

Effects of Mg Added to Ca-Free Solution

TAENIA   It is known that exposure to Ca-deficient or Ca-free solution causes depolarization of the membrane and a high frequency spike discharge,

which becomes gradually oscillatory (Holman, 1958; Bülbring and Kuri-
yama, 1963; Brading et al., 1969 a). The effect produced by removing Ca
is smaller and appears more slowly in Ca-free Krebs solution than in Ca-free
Locke solution (Bülbring and Tomita, 1969 b), probably due to the fact that
Krebs solution contains Mg (1.2 mM). When the spontaneous activity had
disappeared in Ca-free solution, it was usually possible to produce some
oscillatory activity by hyperpolarizing the membrane with inward current
pulses (Fig. 9 a and b). In this condition, depolarizing current pulse pro-
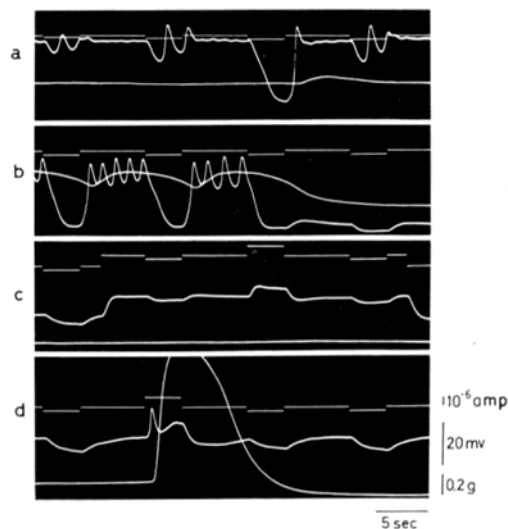

Figure 9.   Effects of Mg (3 mM) in Ca-free Locke solution. Taenia. 30°C. (a) After
30 min in Ca-free Locke solution (the intensity of the first three hyperpolarizing current
pulses was increased stepwise); (b) 3 mM Mg added at the beginning of record, note
repolarization; (c) 10 min later, no response during conditioning depolarization; (d)
10 min after addition of 1 mM Ca. Note suppression of activity by Mg, and recovery of
spike by Ca.

duced only a small electrotonic potential, the low magnitude of which indi-
cated a reduction of the membrane resistance.

The addition of Mg (3–5 mM) to Ca-free Locke solution caused a rapid
repolarization of the membrane (b), but no spike could be evoked although
the solution contained the normal Na concentration (c). After readmission
of Ca (1 mM) to this solution, it became possible to evoke a spike (d).

If Ca was removed and Mg (3–5 mM) was added simultaneously, there
was no depolarization of the membrane and the membrane resistance re-
mained more or less the same. In this solution, the spike could not be elicited,
even during conditioning hyperpolarization or depolarization (Fig. 10).

URETER   Fig. 11 shows results obtained from the ureter. As in the taenia,
the response was completely blocked in Ca-free solution containing 5 mM

Mg, and this was reversible. The membrane potential and resistance remained the same as in normal solution.

Effects of Sr

TAENIA   Ca can be replaced by Sr without blocking the spike (Hotta and Tsukui, 1968). As shown in Fig. 12, total replacement of Ca with the
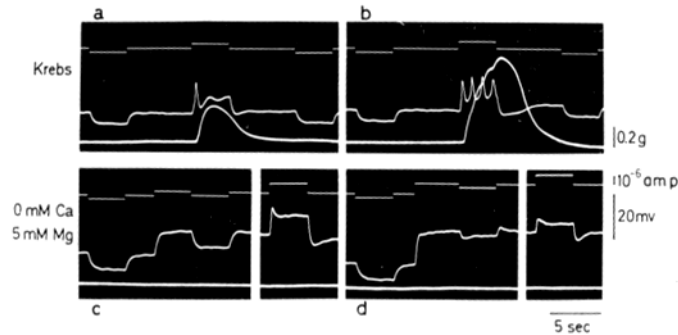

FIGURE 10.   Effects of excess Mg in Ca-free Krebs solution. Taenia. 30°C. (a) and (b), controls in normal Krebs solution. (c) After 20 min in Ca-free Krebs solution containing 5 mM Mg; (d) 10 min later, during conditioning depolarization.
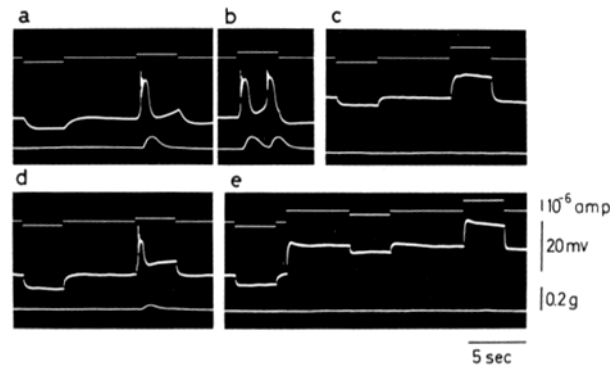

FIGURE 11.   Effects of excess Mg in Ca-free solution. Ureter. 30°C. (a) and (b), controls in normal Krebs solution; (c) after 20 min in 0 mM Ca and 5 mM Mg. (d) recovery in normal Krebs solution (30 min later); (e) after 15 min in 0 mM Ca, 5 mM Mg, during conditioning depolarization. Note no response in excess Mg and 0 Ca.

same amount of Sr did not affect the resting membrane properties or the spike activity.

URETER   Replacement of Ca with Sr reduced the number of repetitive spikes usually to one and prolonged the plateau up to 20 sec (Fig. 13). In some preparations there was oscillatory activity just before the termination of the plateau. The duration of the plateau became slightly shorter when the

stimulus intensity was increased. The contraction was nearly the same as in the normal solution containing Ca.

The upper records in Fig. 14 show another example of the prolongation of the plateau by replacement of Ca with Sr. This effect was gradual and
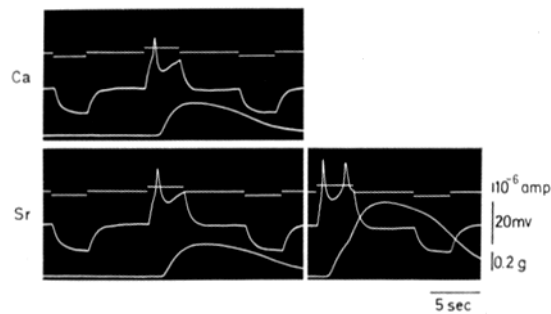

FIGURE 12.   Substitution of Sr for Ca in Krebs solution. Taenia. 24°C. Upper record, control in normal Krebs. Lower record, after 20 min in 0 Ca and 2.5 mM Sr. Note similar responses in both solutions.
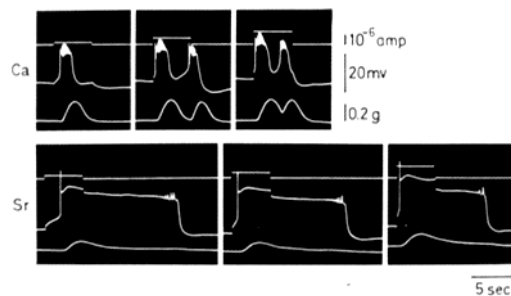

FIGURE 13. Substitution of Sr for Ca in Krebs solution. Ureter. 31°C. Top, controls in normal Krebs solution. Bottom, after 20 min in 0 Ca and 2.5 mM Sr. Note prolongation of plateau when Ca is replaced by Sr.

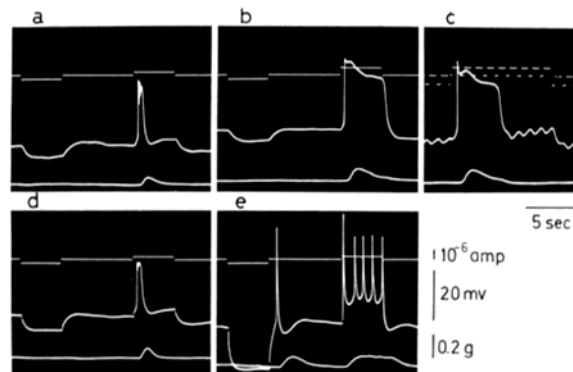FIGURE 14.   Electrotonic potentials during plateau and effects of Na-free solutions on plateau prolonged by Sr. Ureter. 32°C. (a) Control in normal Krebs solution; (b) 25 min after substitution of Sr for Ca; (c) electrotonic potentials produced by short current pulses; (d) recovery in normal Krebs solution; (e) 20 min after replacing NaCl with sucrose in the presence of 0 mM Ca and 2.5 mM Sr. See text for detail.

reached a steady state after about 10 min at 30°C. When short current pulses were superimposed on the stimulating pulses it could be shown that the electrotonic potential nearly disappeared during the plateau phase, indicating a large increase in the membrane conductance.

When NaCl was replaced with sucrose or Tris and Ca was replaced with Sr, the plateau was diminished and only the spike component was produced by electrical stimulation (Fig. 14). The tendency to repetitive spike activity was less in Tris solution than in sucrose solution.

DISCUSSION

The Electrotonic Potential

The properties of the electrotonic potential are very similar in the taenia and in the ureter. There is no doubt that both tissues have cable-like properties. The time course of the electrotonic potential recorded in the present experiments is much slower than in the previous experiments in which the response to extrapolar polarization was observed (Tomita, 1966; Abe and Tomita, 1968). After 1 hr in the double sucrose-gap, the electrotonic potential is roughly 10 times slower than that previously reported (time constant of about 100 msec). Many factors seem to slow the time course of the electrotonic potential in the double sucrose-gap recording.

(a) A high membrane resistance at low temperature (22–26°C) in the present experiments is obviously one of the reasons for the slowness.

(b) The spatial decay of the electrotonic potential is another factor. However, when the center pool is 1–2 mm in length, the difference between the electrotonic potentials recorded intracellularly and by the sucrose-gap method is not very large. Therefore, the spatial decay within the center pool is small and the distortion by the sucrose-gap recording is not serious. The large distortion of the spike shape in the sucrose-gap recording compared with that of the electrotonic potential may be due to temporal dispersion of the spike activity in different bundles, while all bundles are polarized simultaneously to a similar magnitude by current pulses.

(c) The fact that the tissue is immersed in sucrose solution at both sides of the center pool is probably the main factor affecting the electrotonic potential and the spike activity. In the lobster giant axon, a 20–60 mv higher membrane potential was observed by the sucrose-gap method than by the intracellular microelectrode recording (Julian et al., 1962), and this was explained by the effect of the loop currents arising from the liquid junction potentials between sucrose solution and seawater (Blaustein and Goldman, 1966). The same factor may contribute to the hyperpolarization of the membrane in the present experiments. The lack of potassium and sodium in the sucrose solution may also hyperpolarize the membrane of the cells immersed in sucrose solution. Hyperpolarization would raise the threshold

and suppress the spontaneous activity. The membrane resistance of the cells immersed in sucrose solution seems to be very high, because a dilution of Locke solution to one-tenth with sucrose solution increased the electrotonic potential about three times in amplitude.

The largest IR drop across the cell membrane occurs apparently at the junction between Locke and sucrose solutions where the two solutions are probably mixed. The time course of the electrotonic potential at this point of the tissue would then be the main determining factor for the slowness of the recorded electrotonic potential. However, as shown by a simultaneous intracellular recording, the electrotonic potential and the evoked spike recorded by the double sucrose-gap method can be taken as a transmembrane response in the cells immersed in a test solution in the center pool.

Action Potential

In the taenia, Na is not essential for the spike generation. The spike can be evoked in Na-free solution. Furthermore, since the spike is larger and sharper in low Na or Na-free solution than in normal solution, the inward movement of Na ions may not substantially contribute to the spike even when the external Na concentration is normal. Ca ions are probably the main carrier of the inward current during the spike, as previously suggested (Brading et al., 1969 *b*). This conclusion is also supported by the finding that, when the membrane potential is kept normal by the addition of Mg ions, no spike can be produced in Ca-free solution containing the normal Na concentration but that addition of Ca restores the spike.

The depolarization of the taenia membrane observed in Ca-free solution may be due to an increase in Na conductance, which is controlled by Ca bound in the membrane (Brading et al., 1969 *a*, *b*), as in crayfish muscle fibers (Reuben, Brandt, Girardier, and Grundfest, 1967). Mg appears to be able to replace Ca at this site and to decrease the Na conductance of the membrane. However, Mg cannot replace Ca for the spike, probably because it is unable to cross the membrane.

In the ureter, the spike component is affected in the same way as the spike of the taenia when the external Na and Ca concentrations are changed. Therefore, the spike component is probably also due to Ca entry. On the other hand, the plateau component may be due to an increase in the Na conductance of the membrane. This is indicated by the observation that the plateau is abolished by the removal of Na from the external solution. However, the plateau, though Na-sensitive, is not affected by tetrodotoxin (Kuriyama et al., 1967 *a*). In the cat ureter, it is also suggested that both Ca and Na contribute to the action potential, though it does not have a clear plateau component (Kobayashi, 1969).

It is possible to speculate that, if the membrane-bound Ca is released and

the site remains only transiently unoccupied, the Ca permeability of the membrane at this site would be increased, and Ca ions would cross the membrane to produce a spike with a short duration. On the other hand, if the site remains unoccupied by Ca for some time, then the Na permeability of the membrane might be increased, and now Na ions carry the inward current. This could be an explanation for the plateau component in the ureter, and also for the maintained depolarization which occurs in the taenia in Ca-free solution. Since repetitive spikes can be produced during the plateau in the ureter in normal solution, there are probably two different membrane sites, one for the spike generation involving Ca entry, and another for the plateau formation involving Na entry, both being controlled by the membrane-bound Ca.

Sr can replace Ca for the spike in the taenia, and also for the spike component in the ureter. However, Sr seems to affect the process which controls Na conductance in the ureter, and thus Sr increases the duration of the plateau.

The electrical activity in the two smooth muscles which have been investigated is different. The taenia has the spike-type action potential which depends on external Ca, and the ureter has the action potential composed of Ca-sensitive spikes and a Na-sensitive plateau. Different mechanisms seem to operate in the taenia and the ureter under physiological conditions, though the fundamental mechanism by which Ca controls the ion permeability of the cell membrane may be similar.

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