The Effects of Mechanical Stimulation on Some Electrical Properties of Axons

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ABSTRACT Rapid, short duration mechanical compression of lobster giant axons by a crystal-driven stylus produces a depolarization and an increase in membrane conductance which develop immediately with compression but take several seconds to recover. The conductance increase occurs even when the depolarization is prevented electrically. If sodium is removed from the external medium or if procaine is added to it, compression produces almost no depolarization. Small bundles of myelinated frog fibers are depolarized by rapid compression but recover very rapidly (milliseconds); "off" responses are occasionally seen. The results are discussed in terms of the mechanoelectric transducer behavior of an axon membrane.

INTRODUCTION

Many cells have the property of producing electrical changes in response to mechanical stimuli. In mechanoreceptors this property is highly developed and these changes can give rise to nerve impulses. Generally, a mechanoreceptor includes a transformer element which modifies the applied stimulus, a transducer element by which the stimulus is converted into an electrical change, and an electrical element in which the electrical change is converted into a nerve impulse (Gray, 1959). However, these elements are not necessarily present as separate structures. The cutaneous nerves of mammalian skin end in arborizations of fine, naked filaments (Weddell, Pallie, and Palmer, 1954), and corneal nerve endings appear simple in structure. On the other hand, the cochlea and the Pacinian corpuscle are examples of highly complicated receptor devices.

Studies have been carried out on a variety of mechanoreceptors, including the frog muscle spindle (Katz, 1950), a crustacean stretch receptor (Eyzaguirre and Kuffler, 1955), an insect mechanoreceptor (Wolbarsht, 1960), and the Pacinian corpuscle of the cat mesentery (Gray, 1959; Loewenstein, 1959). Recently, Hunt and Takeuchi (1962) have presented evidence indi-

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cating that the non-myelinated axon ending of the Pacinian corpuscle can conduct impulses, which suggests that this part of the axon membrane may not be very different in its characteristics from the axon membrane exposed at the centrally located nodes. It is now generally considered that the transducer of these receptors consists of a semipermeable, polarized cell membrane which reacts to mechanical stimulation by becoming depolarized. Katz (1950) has pointed out that such depolarzatton could be produced by a mechanical stimulus through a change in membrane resistance or capacitance, or through a chemical reaction which might act directly or cause the release of a transmitter agent. One should add to this list the possibility of a streaming potential due to fluid transfer through a charged membrane. The first mentioned possibility is regarded as the most likely, but, so far, no direct evidence for this view has been obtained. A similar interpretation has been offered for the hair cells of the cochlea (Davis, 1954) and the lateral line organ (Kuiper, 1956).

It has been long known that nerve fibers can be excited by mechanical stimuli (Tigerstedt, 1880), and it has been shown that short mechanical stimuli act like cathodal electric shocks (Rosenblueth, Buylla, and Ramos, 1953). Since mechanoreceptors seem to contain a nerve fiber or termination, it is tempting to regard this fiber as providing the transducer membrane. One may then expect the study of the mechanoelectrical properties of an axon to shed light on the behavior of the transducer element of mechanoreceptors.

For investigative purposes, a single unmyelinated axon has the apparent advantage of being geometrically simple and relatively free from structures which could modify mechanical stimuli. Further, a good deal is known about its electrical and structural properties. The giant axon of the lobster, *Homarus americanus*, is particularly suitable since it is relatively large, easily dissected, and can be studied electrically without the use of internal electrodes (Julian and Goldman, 1960) whose presence poses serious problems when mechanical forces and displacements are applied. Most of the experiments reported here were made with this preparation. Some were carried out using small bundles of fibers from the sciatic nerve of the frog in which the responses differ in certain ways from those of the lobster axon. The results are therefore included in spite of the fact that the preparation was not suitable for good potential or impedance measurements. A preliminary account of this work has already been given (Goldman and Julian, 1960).

METHODS

Single giant axons were dissected from the circumesophageal connectives of the lobster, *Homarus americanus*, by a method quite similar to the one given by Wright and Reuben (1958). In this way, a single nerve fiber about 100 μ in diameter and

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3 or 4 cm long could be obtained. About twenty-five experiments were carried out on this single axon preparation. The composition of the artificial sea water used to bathe the fibers was the same as that given by Dalton (1958).

Fig. 1 is a diagram of the recording and stimulating apparatus. The axon was mounted in a lucite chamber in such a way that a central region rested on a smooth base, also of lucite. Thin vaseline seals (about 250 μ thick) were then applied around the axon as shown in the diagram leaving a gap about 1 mm wide. Sea water was kept in this central pool and isotonic potassium chloride was used to depolarize the ends. In between, the axon was perfused with a very low conductance solution of

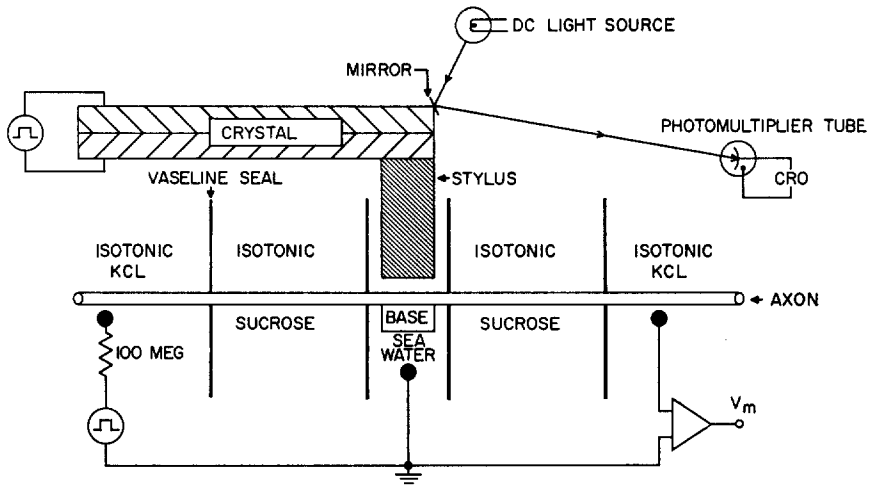

FIGURE 1. Schematic of experimental arrangement. Width of central gap, diameter of glass stylus, and width of base all about 1 mm. Width of isotonic sucrose pools 2 to 3 mm. Black, solid circles represent reversible silver-silver chloride electrodes.

isotonic sucrose. This procedure raised the external leakage resistance to such a high value that essentially full sized resting and action potentials could be recorded from the central segment (Stämpfli, 1954; Julian and Goldman, 1960).

Rectangular current pulses were injected at one end as shown in the diagram to stimulate or polarize the central section of axon.

A bridge method was used to measure membrane impedance. The AC was injected through the stimulating electrode and the central segment of the axon then formed one arm of the bridge. The balancing arm consisted of a small fixed, series resistance and a variable parallel resistance-capacitance combination. The peak to peak AC voltage across the membrane was never allowed to exceed 2 mv. Most of the measurements were made at 200 CPS.

Mechanical stimuli were generated by delivering rectangular voltage pulses to a suitably damped Rochelle salt bimorph having three corners fixed and one free to move. Displacement of the free corner was directly proportional to the amplitude of the voltage pulse up to a safe maximum of about 15 μ. A glass stylus, 1 cm long, was fixed to the movable corner; the flattened tip, about 1 mm in diameter, was

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gently curved in the direction along the axon so that no sharp bends were produced when the axon was compressed. The crystal was so mounted that the stylus was centered over the axon and was lowered until its tip made contact. When the stylus was excited with a rectangular pulse, the time necessary for it to reach 90 per cent of its final displacement value was about 200 μsec. By cementing a tiny mirror to the movable corner of the crystal, movement of the stylus could be recorded photoelectrically. The bottom trace in Fig. 2 shows the movement of the crystal as recorded by a photomultiplier tube when the crystal was excited by a rectangular

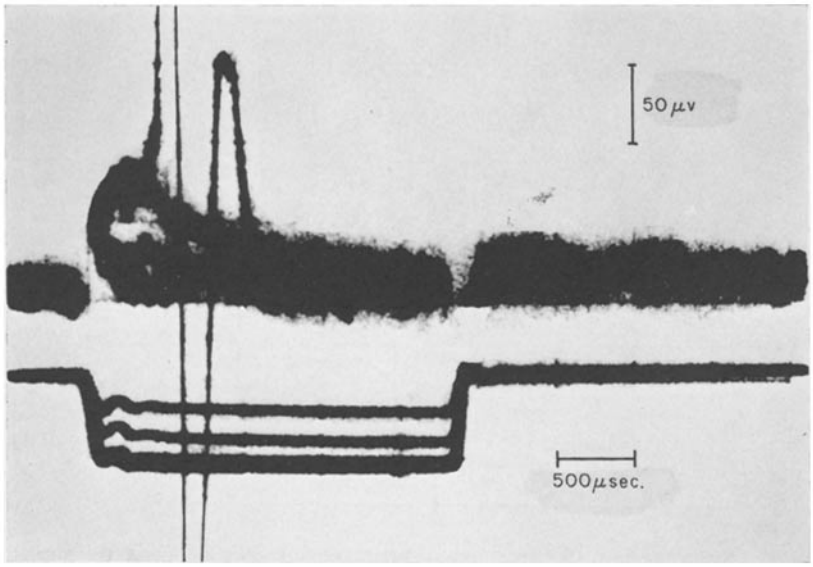

FIGURE 2. Response of filament of frog fibers to mechanical stimulation. Upper trace shows potential response; lower trace time course of mechanical pulse. Gaps in potential record at on and off of mechanical pulse due to capacitative coupling transients. Responses to four mechanical pulses are shown, though difference in amplitude between third and fourth pulse is hardly noticeable.

voltage pulse. The practical upper limit for stimulus duration was about 10 msec. Durations much longer than this were apt to damage the crystal especially at large amplitudes. The axon was observed through a dissecting microscope along the direction perpendicular to the plane of the axon and stylus.

The composition of the solution bathing the central gap could be changed as desired. In some experiments the sodium chloride in the artificial sea water was replaced by choline chloride. In other experiments sufficient procaine hydrochloride was dissolved in artificial sea water to make a solution of 0.1 per cent concentration. The pH of this procaine–sea water solution was adjusted to about 7.9 with sodium hydroxide. All experiments were performed at room temperature.

Nineteen experiments were made with filaments of about five fibers dissected from a sciatic nerve of the frog, *Rana pipiens*. Recording and mechanical stimulation were much the same as for single fibers except that mineral oil was used in place of the

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sucrose solution, and the base was a platinum plate used to record the electrical response of the region of nerve being mechanically stimulated. Platinum wires were used to make contact with the ends of the filament. The recording system was AC-coupled (coupling time constant, 200 msec.). The central gap and the ends of the filament were bathed with a Ringer solution.

RESULTS

Preparations could be maintained for up to an hour provided that they were not stimulated at too high a rate (2 to 3 per minute). Responses to mechanical stimuli were easily obtained but were difficult to reproduce precisely. This may have been due to problems of positioning of the stylus relative to the fibers or to a drift in their characteristics. In any case it was not usually possible to obtain reproducible quantitative relations between stylus displacement and the responses of the fibers to better than about 30 per cent, although it was obvious that greater responses were obtained from the larger stimuli.

The Response of Frog Nerve

Filaments of frog sciatic nerve containing five or six fibers, about 10 μ in diameter, were mechanically stimulated as described. The upper trace in Fig. 2 is the potential difference between the plate electrode and a distal electrode about 5 mm away in a typical experiment. The lower trace is the time course of the stylus at four different displacements—increasing amplitude of displacement being shown as a downward movement. The amplitudes of the third and fourth displacements were not different enough to resolve the bottom trace into two distinct lines.

At the beginning of the stimulus a non-propagated response was produced which increased as the displacement of the stylus was increased. The fourth mechanical pulse, just slightly greater in amplitude than the third, produced a response large enough to initiate a triphasic action potential—seen coming off near the crest of the local response. With large displacements, a local response was sometimes seen at the end of the mechanical pulse. In a few cases this was large enough to set off an action potential also. It should be noticed that the local response decayed even though the displacement was maintained.

A short cathodal electric stimulus delivered near the peak of a mechanically induced local response could initiate an action potential when neither stimulus was sufficient by itself. The amplitude of stylus displacement necessary to initiate an action potential was rather variable (2 to 5μ).

In Fig. 2, the gaps in the upper voltage trace are due to capacitative coupling between crystal electrodes and recording electrodes, which led to the appearance of fast transients at the beginning and end of the mechanical pulse. Control experiments showed that these transients had no effect on the

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nerve fibers. The idea that mechanical stimulation produced only transient changes in the excitability of a frog fiber was explored by comparing threshold effects produced by mechanical and cathodal electric conditioning pulses. In Fig. 3, the results of such an experiment obtained from the same fiber are shown. Clearly, in the case of electrical conditioning, threshold was lowered throughout the period of current flow. However, a decrease in threshold occurred only near the beginning and end of the mechanical conditioning

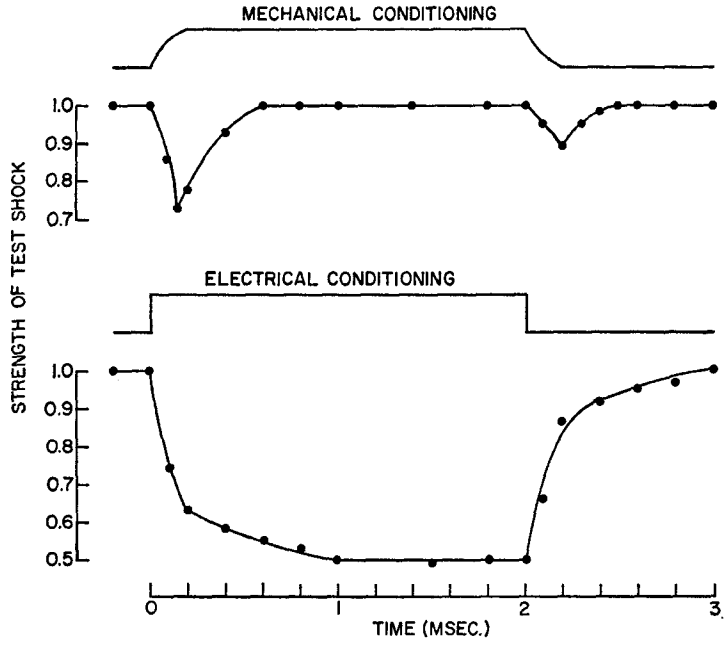

FIGURE 3. Effects of mechanical and electrical conditioning pulses on threshold of frog fiber. Test shock was a 10 μsec. electrical pulse. Strength of test shock plotted as fraction of initial value. Mechanical pulse is rounded at the on and off because of relatively slow rise time of stylus. Duration of pulses in each case was 2 μsec.

pulse; the threshold returned to its initial value during the period of maintained displacement. Some of the transient effects of mechanically stimulating frog fibers could have been due to changes of the stylus-axon relationship during the period of maintained displacement. That is, constant deformation would not be achieved because, for example, the fibers might move relative to each other and to the stylus. On the other hand, an off response would not be expected if fibers had already returned to their initial conditions unless displaced anew during the upward motion of the stylus. Transient effects were the only kind observed in these experiments, even when the stylus was advanced so that the fiber bundle was under considerable steady pressure.

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Mechanical Excitation of Single Lobster Giant Axons

Fig. 4A shows an action potential elicited from a single axon by a mechanical stimulus. The threshold displacement amplitude for the axons was 10 to 15 μ at the velocities used (about 5 cm/sec.). Slow compression of the axon

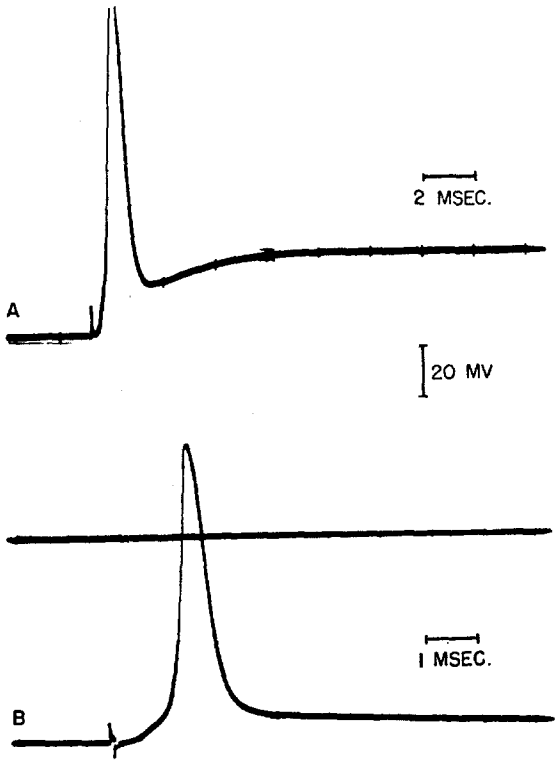

FIGURE 4. Part A shows action potential elicited by short mechanical pulse, and part B an action potential set off by electrical shock in single lobster giant axons. Small stimulus shock artifacts are visible just before spikes in both records. Straight horizontal line in part B sets level of zero membrane potential difference.

(stylus movement hand-controlled) did not produce a depolarization. The most striking effect produced by mechanical stimulation of lobster axons was the long time (several seconds) necessary for repolarization. Visual observation of axons under a microscope showed that distorted axons recovered their cylindrical shape over a period of several seconds, seemingly parallel to the recovery of the potential. This was true whether the stimulus duration was 0.5 msec. or 10 msec. Mechanical shocks of sufficient amplitude to set off an action potential were not ordinarily used since repolarization to the prestimulus level, in these cases, was apt not to be complete.

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In Fig. 4B, an action potential from a single giant axon excited by a short electric shock is shown for comparative purposes. Notice that the time scales in A and B are different. As can be seen from B, the lobster giant axon does not show an undershoot or transient hyperpolarization following the spike. However, the slow return of the potential to the resting level after the phase of rapid repolarization following an electrical stimulus is not at all comparable in either magnitude or time course to that following a short mechanical stimulus. Off responses to mechanical stimuli were never found.

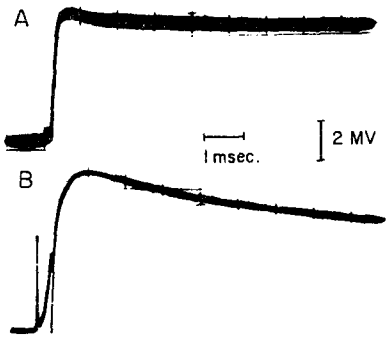

FIGURE 5. Difference between depolarization produced in lobster giant axon by long and short mechanical pulses. In part A, a 10 msec. pulse was used; in part B, an 0.5 msec. pulse. Capacitative coupling transients appearing at on and off of pulse are visible in part B. Depolarization is shown as upward deflection.

The Difference in Depolarizations Produced by Short and Long Mechanical Pulses

If the mechanical displacement was maintained for 10 msec., the depolarization produced remained nearly constant for the duration of the pulse and then began to recover slowly when the stylus returned to its resting position. However, the recovery following a short mechanical pulse of about 0.5 msec. duration was somewhat more rapid. This effect is demonstrated in Fig. 5. In A, the depolarization is well maintained during a 10 msec. mechanical pulse. In B, a short, 0.5 msec., mechanical pulse was used and repolarization can be seen to begin soon after. Observation at greater sweep speeds showed that the speed of depolarization followed closely the speed of the stylus movement.

Impedance Changes Produced by Mechanical Stimulation

In Fig. 6A, the upper trace is the change in membrane potential produced by a 10 msec. mechanical pulse. The lower trace is the bridge output. There is a sudden unbalance coincident with the drop in membrane potential

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followed by a slow recovery which parallels the return of the membrane potential to its former level.

The effect of the mechanical stimulus on the membrane resistance and capacitance characteristics was determined by initially unbalancing the bridge by increasing or decreasing the parallel resistance or capacitance in the balance arm. Mechanical stimuli were then delivered and their effect on bridge unbalance recorded. Only if the parallel resistance in the balance arm were decreased could the bridge output be brought to a balanced condition by a mechanical stimulus; capacitance changes were without significant effect. In Fig. 6B is shown the balancing effect of a 10 msec. mechanical pulse coincident with the drop in membrane potential when the bridge was

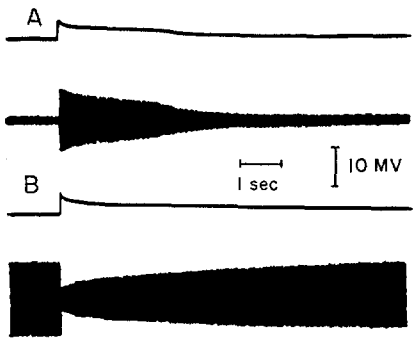

FIGURE 6. Impedance change produced in lobster giant axon by mechanical stimulation. Upper traces, in each part, show membrane potential, and lower traces are time courses of associated impedance change. 10 msec. mechanical pulses were used. Bridge frequency 200 CPS. Part A shows bridge initially balanced. In part B, the bridge was previously unbalanced by decreasing series resistance in the balancing arm. Depolarization shown as upward deflection.

initially unbalanced by decreasing the parallel resistance in the balance arm. Similar results were obtained at 20 and 1000 CPS.

Comparison of Decrease in Membrane Resistance Produced by Mechanical and Electrical Stimuli

Fig. 7A shows a depolarization of about 10 mv produced by a short mechanical pulse. The bottom trace is the time course of the associated decrease in membrane resistance. After the membrane potential and the bridge balance had regained their initial levels, sufficient current was passed through the membrane to depolarize it again by about 10 mv. The results are shown in Fig. 7B in which the upper trace is the course of the membrane potential and the lower, the time course of the associated decrease in membrane resistance. Clearly, the magnitude of the decrease in membrane resistance is

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considerably greater when a subthreshold depolarization is induced by a mechanical pulse than when produced by an electrical one. This was so to about the same extent in all cases in which this comparison was made.

The Direct Effect of a Mechanical Stimulus on the Membrane Resistance

In Fig. 8, the depolarizations produced by three short mechanical stimuli are shown (labeled *MS*). In the first two, the membrane potential was brought up by a hyperpolarizing electric current (*HP* on) to a level considerably

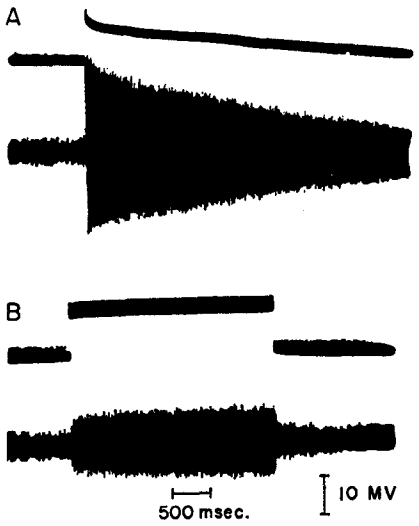

FIGURE 7. Comparison of impedance changes produced by mechanically and electrically induced depolarizations of similar size. A short mechanical pulse was used in part A. In part B, a cathodal electric current was used to produce depolarization of size similar to that shown initially in part A. Bridge initially balanced in both cases. Bridge frequency 200 CPS. Depolarization shown as upward deflection.

above the resting and held there for 1 second, and then the current was turned off (*HP* off). The membrane potential fell, undershot the resting level, and then returned slowly to the initial level just as it did in the third response, which was taken without injecting a hyperpolarizing current. The effect produced by a mechanical stimulus is therefore not cancelled by hyperpolarizing the membrane with an electric current. That is, the mechanical stimulus produces a change in the membrane which is not completely dependent on a potential change, and the time needed to reverse this mechanical effect is much longer than the membrane electrical time constant.

It was also necessary to determine whether or not the mechanically produced decrease in membrane resistance would still occur if the membrane

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potential were prevented from changing. Ideally, this would require that the membrane potential be clamped. It was not possible to establish uniform potential control over the central segment of membrane, but changes in membrane potential were minimized by including the central segment of membrane in the negative feedback loop of an operational amplifier. The

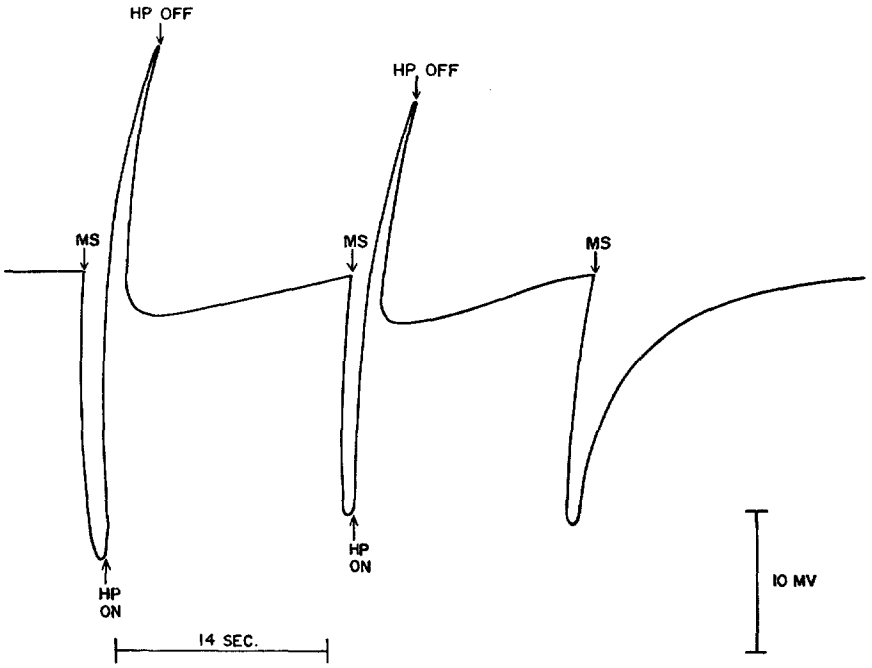

FIGURE 8. Effect of electrical hyperpolarization during course of mechanically produced depolarizations. Depolarization shown as downward deflection, hyperpolarization as upward deflection. *MS* indicates times when short mechanical stimuli were delivered. "*HP* on" and "*HP* off" show when hyperpolarizing current was turned on and off; duration of current flow was 1 second. These are tracings of original records obtained from a curvilinear recorder having a response time of about 400 msec. (0.1 to 0.9).

frequency response of the amplifier was modified in such a way that the 200 CPS signal used to measure membrane resistance was not clamped out. This resulted in poor control of the membrane potential during the initial part of the mechanical effect. Nevertheless, membrane potential changes produced by the mechanical stimulus could be minimized without changing very much the size or time course of the associated decrease in membrane resistance (Fig. 9). The results show that the decrease in membrane resistance is neither produced nor strongly influenced by changes in membrane potential, but is a direct result of the mechanical stimulus.

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The Effect of Substituting Choline for Sodium

The sodium in the sea water in the central gap was replaced by choline; mechanical stimuli of constant magnitude were then delivered to the axon. After a constant response was obtained, the central gap was gently washed with a normal sodium-containing sea water solution. Without changing the magnitude of the mechanical pulse, the response to this solution was obtained. Figs. 10A and B are the responses of two different axons to this procedure. It can be seen that the responses in choline–sea water solutions are much smaller than those obtained in normal sea water.

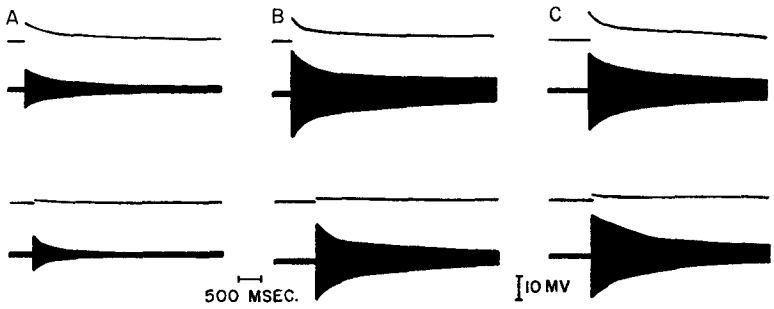

FIGURE 9. Effect of minimizing potential change on decrease in membrane resistance produced by mechanical stimulus. Parts A, B, and C show results from three different experiments. In each part, the upper records show magnitude of impedance change when no attempt was made to control potential. Lower records taken immediately after upper, but with current feedback used to minimize potential change produced by short mechanical stimuli of constant strength. Bridge output records retouched for greater clarity.

The slight rise in membrane potential occurring when the central gap was washed with normal sea water may possibly be due to the removal of a small accumulation of potassium around the outside of the axon. The central gap was not perfused during the time it contained choline–sea water in order to prevent any change in the stylus-axon relationship.

The Effects of Procaine

Procaine causes a reduction in the amount and rate of development of the currents which occur during a depolarizing voltage step applied to a squid axon (Taylor, 1959). The effect of an 0.1 per cent concentration of procaine in the sea water perfusing the central gap on the depolarization caused by a mechanical pulse is of interest because of its effect in inhibiting permeability changes in nerve membranes.

In Fig. 10C, the first trace is a response produced while the axon was in normal sea water. The procaine–sea water solution was then applied and

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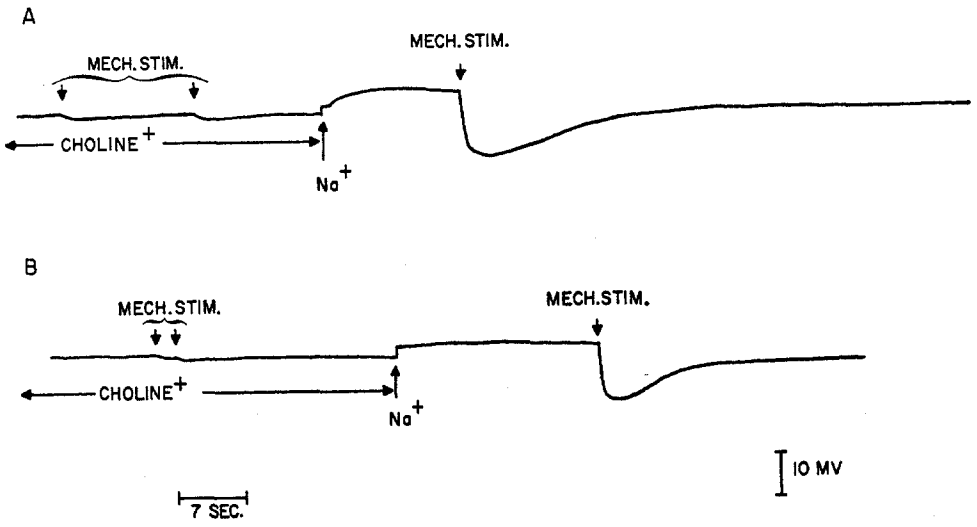
about 10 minutes later mechanical stimuli of the same strength were delivered to the axon, as shown in the middle record. Procaine–sea water was then replaced by normal sea water and about 10 minutes later the trace labeled "after" was obtained. Clearly, the responses are markedly decreased in size during the time that procaine is in the sea water. However, recovery is not complete 10 minutes after procaine has been removed. In the voltage-clamped squid axon, procaine effects are also slowly reversible after its removal. In this experiment, the resting potential of the axon was not appreciably changed.



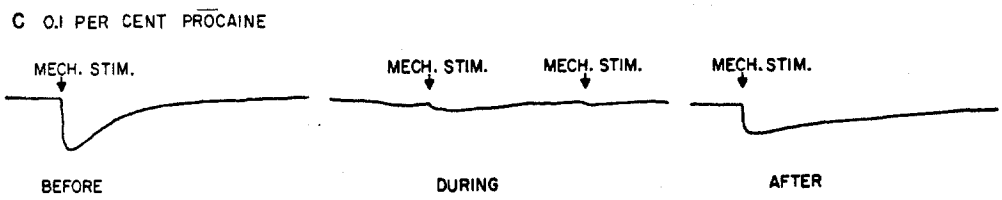


FIGURE 10. Parts A and B show results from two different experiments in which choline was substituted for sodium in the artificial sea water. In part C, the effect of adding 0.1 per cent procaine to artificial sea water is shown. These are tracings of original records obtained from a curvilinear recorder having a response time of about 400 msec. (0.1 to 0.9). Depolarizations are shown as downward deflections. "Mech. stim." refers to points at which short mechanical pulses were delivered.

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DISCUSSION

The transducer behavior of an axon consists in the appearance of an electrical output, a depolarization, in response to a mechanical input, a rapid displacement of the membrane. As was mentioned earlier, there are several ways in which mechanical changes in a membrane can lead to a depolarization. On the basis of the experiments reported here, streaming potentials can be excluded from serious consideration. If fluid were driven through a charged membrane, there should be a reversal in the sign of the potential change during recovery; no such reversal is observed. There is also direct evidence that the membrane capacitance does not change significantly at any time during the entire depolarization and recovery period. There is, on the other hand, direct evidence for a conductance increase. As to chemical phenomena, there does not seem to be any reason to consider the release of chemical agents in these experiments. One can, of course, treat changes in the position of molecular elements in response to a distortion of the membrane as a chemical reaction, but this point of view is probably useful chiefly in a detailed study of the molecular structure of the membrane.

The response of the axon to mechanical stimulation is thus an increase in membrane conductance accompanied by a depolarization. The exact mechanism by which this is accomplished is not yet clear, but there are certain lines of reasoning which can be followed up. Bending of the membrane is unlikely to be of importance since a significant structural change in a flexible membrane of the order of 100A thick would require the appearance of a curvature of the same order of magnitude, far sharper than is possible with the experimental system used. On the other hand, when an axon is compressed, the contents of the region under the stylus are distorted and there will be a tendency for fluid to escape through the membrane, for the axoplasm to move to an adjacent region, and for the membrane to stretch. The more rapid the process, the less opportunity there will be for fluid or axoplasm transfer to occur and the more the membrane surface area will increase. Such an increase will tend to separate the molecular elements of the membrane, either uniformly or at certain preferred regions. This process would be expected to increase the permeability of the membrane in some respects at least and thus increase the membrane conductance. If, further, there is a change in relative ion permeabilities, a change in membrane potential would also result. The fact that 0.1 per cent procaine can block the depolarization indicates that the membrane changes are not so drastic that the system ceases qualitatively to follow its normal type of behavior. This conclusion is also borne out by the fact that depolarizations of mechanical and electrical origin are interchangeable in their effects on the axon and that complete recovery occurs.

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The recovery process presumably depends on such elastic and other forces as may tend to restore the membrane area to its original value. The return of the axon to its original shape would involve primarily the flow of axoplasm, which may not necessarily have the same time characteristics as the recovery of the membrane although this appears to be so in the lobster axon.

Examination of the problem of relative ion permeability changes does not, from these experiments, yield a clear answer. Removal of sodium from the medium does reduce the mechanically produced depolarization to a very small value and this certainly suggests that permeability changes to sodium are important. On the other hand, the sodium permeability is normally small relative to that of potassium and a subthreshold depolarization due to an increase in sodium permeability alone should result only in a small increase in conductance of the membrane. Permeability changes to other ions cannot, therefore, be excluded, and this situation is quite similar to that in the Pacinian corpuscle (Diamond, Gray, and Inman, 1958).

To estimate the sensitivity of the transducer one may carry out a simple calculation based on a cylindrical tube with very thin, weak walls filled with an incompressible viscous fluid. The increase in surface area of such a tube when subjected to lateral compression without change of volume turns out to be roughly proportional, for moderate compressions, to the square of the fractional change in spacing between the stylus, initially in contact with the cylinder, and the base plate. A 10 per cent compression produces about an 0.5 per cent increase in area and a 20 per cent compression over 2 per cent increase. In the lobster axon a 10 per cent compression results in a depolarization of roughly 10 mv, indicating that the ion permeabilities must be quite sensitive to changes in membrane area. Hubbard's (1958) experiments on the displacement of the various parts of the Pacinian corpuscle showed that the axon terminal portion, about 3 μ thick, produced a threshold value of receptor potential at a compression so small as to be below the 0.5 μ limit of resolution of the optical measuring system.

It is therefore plausible to suppose that the transducer action of the axon is as follows: compression of axon, stretching of membrane, increase in ion permeabilities with a change in their relative values, depolarization and, finally, a mutual readjustment of conductance and potential. The last steps can be avoided by maintaining the membrane potential near its resting value during the mechanical stimulus and there remains the conductance increase produced directly by the stretching of the membrane. This is appreciably greater than that produced by a depolarization of this magnitude when caused by an electric current alone.

The preceding discussion has been based primarily on observations with the lobster axon. The situation in the frog fiber is more complicated. The

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elastic properties of the myelin sheath may be very different from those of the sheath of the lobster axon. The nodal regions are appreciably less extensible than are the internodes (Schneider, 1952). The external diameter is not uniform, being reduced at the nodes. Further, the preparation used here contained several fibers which could easily have taken up positions relative to each other which could be changed by the motion of the stylus. The major differences between the response of the lobster axon and the frog fiber bundle were the rapid recovery and presence of occasional off responses in the latter. The rapid recovery may well be due to differences in the factors mentioned. The off responses could arise from a mechanical action due to the sudden release of the stylus. However, more work needs to be done to clear this up. The observation (Gray and Ritchie, 1954) that rapid stretching of single frog fibers produced no detectable depolarization is rather difficult to compare with our experiments because of the differences in the mechanics of the apparatus and procedure. The actual stretching of the nodes was probably considerably less than the average (5 per cent increase in 0.7 msec.) for the fiber. The question could best be settled by direct comparative experiments.

The idea that the transducer element of mechanoreceptors consists of a polarized membrane which is depolarized by stretching is a very attractive one. It appears to be consistent with indirect observations on mechanoreceptors and is considerably strengthened by the experiments reported here. The evidence further indicates that the depolarization arises from an increase in ion permeabilities produced by separation of the elements of the membrane. An understanding of the molecular mechanisms especially in relation to permeabilities to specific ions will require further experimental study.

The opinions or assertions expressed herein are the private ones of the authors and are not to be construed as official or reflecting the views of the Navy Department or the naval service at large.

Received for publication, July 16, 1962.

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