AN ANALYSIS OF EXTRACELLULAR POTENTIALS FROM SINGLE NEURONS IN THE LATERAL GENICULATE NUCLEUS OF THE CAT

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ABSTRACT

The lateral geniculate nucleus of the cat was explored with micropipettes having submicroscopic tips. The only reliably recorded intracellular activity was from axons. Following orthodromic stimulation, the potentials recorded by the extracellular electrodes registered the net flow of current across the soma-dendritic membrane of the principal cell bodies. The current has three phases of flow away from the soma-dendritic membrane followed by a flow of current toward this membrane. The first component is ascribed to synaptic activity. Subsequent components are ascribed to the activity of the initial segment of the axon and a limited area of high threshold membrane on the soma. The evidence is interpreted as suggesting that most of the soma-dendritic membrane is excited synthetically to produce a postsynaptic potential, but is not excited electrically and does not produce a propagating spike.

INTRODUCTION

The use of capillary micropipettes has provided much illuminating information about the physiology of nerve cells. These data have been obtained, primarily, by the use of intracellularly placed electrodes that record changes in membrane potential. Further information about the nature of the activation of the parts of the neuron and the sequence of activation of the parts can be obtained by recording the extracellular potentials. Because of the complicated structure of the neuron, the potential field around a population of somata, axons, and dendrites is complex. As has been shown by Fatt (17), this com-

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plexity makes it difficult to analyze the potential field set up by the parts of the neurons in a population of neurons. However, if the tip of the pipette is assumed to be practically in contact with the soma-dendritic membrane, the analysis of the potential field is simplified. The record will then be caused by the flow of the net membrane current in the extracellular space, if other conditions are fulfilled. Fatt and Katz (18) and Castillo and Katz (9) have employed a method like this for extracellularly recording the flow of current generated by miniature end plate potentials at the myoneural junction. This analysis of the activity of the principal cells of the lateral geniculate nucleus of the cat is based on these assumptions, which have a reasonable experimental basis.

**Methods**

The arrangement of the experiments is shown in Fig. 1. One stimulator, $S_1$, excited the contralateral optic nerve (OT). The technique described by G. H. Bishop and Clare (3) for stimulating the optic nerve was used. The other stimulator, $S_2$, activated some of the fibers of the optic radiation ($R$). A row of eight electrodes 1 mm. apart were inserted in the radiation. Stimuli were applied between odd and even electrodes in the row. The electrodes were made from steel beading needles that were insulated with bakelite varnish to their tips, which were about 100 μ in diameter.

The responses were recorded with two sizes of electrodes. The larger of these was made from either a steel beading needle, like those inserted in the radiation, or from a quartz pipette having an outside diameter at the tip of 75 μ. The quartz pipette was filled with Tyrode's solution, and a 25 μ silver wire was inserted in the tip in order to reduce the electrode's resistance. The responses recorded by the needle and the quartz pipette were the same. This coarse electrode, $P_2$ in Fig. 1, was inserted in the geniculate along a vertical plane of the stereotaxic coordinates and at an angle of 30° anterior to a perpendicular. Recordings from this electrode registered the electrical activity of a large group of neurons.

The other recording electrode, $P_1$, was a machine-drawn glass micropipette of the same type as those employed by Frank and Fuortes (19). Usually it was filled with 3 M KCl. Some of the micropipettes used for extracellular recording were filled with 5 M NaCl. The pipettes were drawn from pyrex 7740 glass tubing that had an outside diameter of 1.2 mm., a wall thickness of 0.3 mm., and a dielectric constant of 5.00. The calculated capacity for such a cylindrical capacitor is 0.40 pico-farad/mm. For the entire length of the micropipette, except for the 2 to 3 mm. length where the taper is the greatest, this value agrees with the measured capacity with less than 10 per cent variation. This agreement indicates that the ratio of outside to inside diameters is relatively constant despite the taper. Since the lateral geniculate (LGN) is 15 ± 1.5 mm. below the surface of the cortex, the capacity across the glass walls of the micropipette in situ is 6.0 pf. This amount of capacity is unavoidable without shielding most of the inserted portion of the micropipette. Shielding, however, was found to introduce additional problems. Electrodes were selected for a d.c. resistance of 15 to 50 MΩ when immersed in 3 M KCl, but often their resistance increased five- to tenfold after insertion in the brain. A probable cause for the increases in resistance
is that the tip of the pipette became plugged, as suggested by Adrian (1). Therefore, the measurements of the resting potentials of impaled neurons were not considered to be accurate because it is likely that unknown tip potentials were present. The micropipettes were inserted vertically in the geniculate. The pia was not cut, nor were the cortex and white matter removed, except in early experiments. Either hydraulically or mechanically driven micromanipulators were employed. Difficulties caused by movements of the brain that were synchronous with pulse or respiration were hardly noticeable after curarization, bilateral pneumothorax, and gentle artificial respiration.

Fig. 1. A schematic representation of the arrangement of the experiments.

Apparently the geometry of the brain is such that the geniculate is remarkably stationary.

A modified MacNichol-Wagner negative capacity preamplifier (27) or, more frequently, a similar preamplifier designed by Mr. A. Bak of this laboratory received the signal, \( E_i \), from a chlorided silver wire in the micropipette. The response of such an input probe to a step in voltage applied between the tip of the micropipette and ground is given by the expression

\[
\frac{A_v}{1 - e^{\frac{-t}{\tau'}} \left(1 + \frac{t}{\tau'}\right)}
\]

for the critically damped case (21). \( A_v \) is the gain of the preamplifier for a d.c. signal, \( t \) is time, and \( \tau' \) is equal to \( \sqrt{\tau R(C_1 + C_2)} \) in which \( \tau \) is a single time constant that describes the response of the preamplifier when the source impedance of the signal at the input is zero, \( R \) is the resistance at the tip of the micropipette, \( C_1 \) is the capacity of the micropipette, and \( C_2 \) is the positive feedback capacity in the circuit. Since \( \tau \) is about 0.4 \( \mu \text{sec.} \) and the other terms are unavoidably large, the frequency response is limited by these factors.
A device suggested by Dr. J. Y. Lettvin was employed for monitoring the fidelity of the recording and measuring the resistance at the tip of the micropipette. A 1 pf condenser was connected to the input of the preamplifier, and a negative-going sawtooth of voltage was applied between this condenser and ground. This produced a constant current pulse of less than $10^{-10}$ amp. which flowed through the micropipette. The voltage pulse that is developed across the resistance at the tip of the micropipette is the same as that which would appear if a square pulse of voltage could be applied to the tip of the pipette in situ. The tip resistance is proportional to the amplitude of the voltage pulse that is developed.

Both signals, $E_1$ and $E_2$, were recorded with reference to a chlorided silver wire in the temporal muscle and appeared on the tube face of a dual-beam oscilloscope. The sweep velocities of both beams were identical. The amplifiers were operated either at a time constant of 0.1 sec. or direct-coupled.

Experiments were performed on about 40 cats under pentobarbital anesthesia. Curarization with intocostrin did not alter the amplitude or configuration of the response to optic nerve stimulation, as recorded by the coarse electrode. The blood pressure was read from a mercury manometer and was about 80 mm. of mercury. Approximately 25 tracts were made by micropipettes in the lateral geniculate of each cat.

RESULTS

The configuration of the orthodromic response recorded by a coarse microelectrode in the lateral geniculate nucleus of the cat has been analyzed by G. H. Bishop and O'Leary (4) and P. O. Bishop (5). They showed that the first two components of the response, a positive followed by a negative wave, register the electrical activity of the optic tract fibers. This portion of the record will be referred to as the tract spike. Within less than a millisecond after the end of the second, or negative, phase of the tract spike, there is another negative-going deflection. This deflection registers the activity of the postsynaptic structures. Examples of these multicellular responses are shown in the lower traces of the photographs of Figs. 2 to 6. Positive deflections are upward in all figures.

If the stimulus to the contralateral optic nerve is submaximal, the slowly conducting tract fibers are not excited, and signs of their activity are absent in the multicellular records. It is then possible to be certain that only the largest group of fibers in the optic tract is excited, as has been shown by G. H. Bishop and Clare (3) and P. O. Bishop, Jeremy, and Lance (6). Therefore, neurons that respond after the end of the tract spike are postsynaptic. The neurons that are labelled as postsynaptic on this basis frequently fire repetitively while presynaptic elements, which fire during the tract spike, do not display repetitive activity after a single stimulus. Further evidence for the validity of this method of identification is furnished by the results of stimulation of the radiation fibers. None of the axons that fired during the tract spike after orthodromic stimulation responded to the antidromic stimulus. About 20 axons were found that responded after the tract spike on orthodromic excitation and also responded
to the antidromic stimulus. Their action potentials were like those shown in Fig. 2.

**Intracellular Recordings.**—With possibly one exception, the only type of intracellular record that could be obtained consistently was of the sort shown in the upper trace of Fig. 2. It is likely that this trace is a record of the potential difference across axonal membrane because a resting potential was obtained, and action potentials of similar time course were recorded from the optic radiation and tract. It is ascribed to a postsynaptic axon because of the repetitive firing and its occurrence after the tract spike of the lower trace. The reduction in amplitude during rapid firing, as displayed by the second response of this axon, has been reported by Tasaki (35). The negative-going pulse at the end of the upper trace is the response of the input circuit to a pulse of constant current (cf. Methods).

**Extracellular Recordings.**—Extracellular responses that lasted over half an hour could be recorded consistently from the micropipette. Only one type of extracellular response was found, probably because other smaller varieties were lost in the noise. An example of this kind of response is shown in the upper trace of Fig. 3 B. Responses of this sort from 15 cells were large enough to permit a detailed analysis. The response consists of three positive-going components followed by a rapidly negative-going component. The frequency response of the input circuit is given by the negative-going pulse, as in Figs. 2, 3, 4, and 6. A record of this type which has been corrected for frequency response is shown in Fig. 9 B. The correction was made by assuming that the response...

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1 The possible exception referred to above is an all-or-none response that appears with a resting potential and has a shape like that of an axonal action potential as recorded by an input circuit with a very poor frequency response. The response to the constant current pulse led to the input is, in fact, poor and shows that the electrode resistance is over 200 MΩ. The questionable responses are recorded from both presynaptic and postsynaptic elements. It is probable that they are axonal action potentials recorded by a micropipette with a plugged tip. However, the micropipette might be recording from inside a small cylindrical neural structure. In this case, the resistance between the tip and the extracellular medium would be given by the product of the internal resistance per unit length and the length constant divided by two. For a structure with the protoplasmic resistivity and membrane resistance of a neuron and a diameter of less than 1 μ, the resistance to the extracellular space would be greater than 70 MΩ. For this calculation, a value of 1000 ohm cm.² was chosen for the specific membrane resistance and 50 ohm cm. was chosen for the protoplasmic resistivity (11). Such a resistance added to the tip resistance of the micropipette would be sufficient to make the response to the constant current pulse appear poor. Therefore, the possibility cannot be excluded that these prolonged potentials are faithfully recorded from fine neural structures and arise, for instance, by electrotonic spread of an axonal action potential into terminal arborization fibers or by antidromic electrotonic spread into dendrites.
to a voltage step, like those in Fig. 3, is a single exponential with a time constant of 250 µsec. Although the response has been shown not to be a single exponential, the assumption does not introduce an error as large as those inherent in the other graphical methods that were tried. The structures that produce this kind of response are postsynaptic since they fire after the tract spike and can fire repetitively to a single stimulus (Fig. 6). Responses that have a similar time course have been reported by Tasaki, Polley, and Orrego (36), who also recorded them from the lateral geniculate with micropipettes like those employed in this study, and by Rose and Mountcastle (33), who recorded from other thalamic neurons. In addition, similar wave forms were observed by Amassian (2) from units in the cerebral cortex, by Svaetichin (34) when he studied the dorsal root ganglion cell, by Granit and Phillips (25) in their study of the Purkinje cell of the cerebellum, and by Patton and Towe (29) working on the Betz cell. Finally, Rayport (32) recorded this kind of response from a cortical neuron and then marked it after penetration. He found the stain in the cell body. These investigators believed that their recordings were extracellular and from soma–dendritic membrane. This is the opinion of the author, too, because the responses are from postsynaptic elements but cannot be found in the radiation and are not recorded with a resting potential. Furthermore, after the
response is first recorded, movement of the micropipette for more than 100 μ,
with respect to the head holder, will frequently increase the amplitude until a
resting potential and an injury discharge appear. Since this response can be
recorded at some distance from the cell and has a constant shape for at least
half an hour, it does not seem likely that the membrane properties have been
considerably altered by the micropipette. Tasaki et al. (36) have published a
record that shows the increase in amplitude produced by advancing the micro-
pipette. The records of Figs. 3 to 6 were obtained from cells that were subse-
quently impaled without additional advancement of the micropipette. This
supports the assumption that the tip of the micropipette was practically in
contact with the cellular membrane when these records were obtained.

It seems probable that the micropipette records from the extracellular field
resulting from the local current flow around the soma–dendritic membrane of
the cell body. This was the conclusion of Tasaki et al. (36). The possibility that
the micropipette is recording from axonal membrane is rejected because no
extracellular recordings of the kind reported here have been obtained from
structures that are composed only of axons. If this conclusion is correct, a
positive-going deflection can be interpreted roughly as a flow of current away
from the soma–dendritic membrane and a negative-going deflection as a flow
of current toward it. The external current flows toward an area of greater
depolarization from one of lesser depolarization. A discussion of the relation
between the recorded voltages and the flow of membrane current will be post-
poned until later.

There are other possibilities that require consideration. One possibility that is sug-
gested by the shape of the records is that they might be the derivative of the action
potential of the cell body. This would be possible if the capacity between the inside
of the micropipette and the inside of the cell body were large enough, for sufficient
current to produce the recorded voltage might then flow across the tip resistance of
the micropipette. The current would have to be about $10^{-10}$ amp. since the amplitude
of the response is approximately 5 mv. and the tip resistance is about 50 MΩ. The
maximum rate of rise of intracellularly recorded action potentials is 250 v./sec. (Fig.
9 A), so the necessary capacity is 0.4 pf. Since the capacity across the walls of the
micropipettes is 0.4 pf/mm., a 1 mm. length of pipette would have to be surrounded
by active membrane. The effect of the membrane capacity of the cell is neglected in
this calculation but would tend to raise the estimate of the necessary capacity. This
possibility does not seem likely for the cell bodies are less than 30 μ in diameter.

Another possibility is that the potential field of a population of neurons that is re-
corded by the coarse electrode might contribute appreciably to the recordings from
the micropipette. This does not seem possible because of the relatively small amplitu-
de of the recordings from the coarse electrode.

Recordings from the same neuron were used to make Figs. 3 to 5 because of
the particularly large amplitude of the response. Most recordings, like Fig. 6,
were of smaller amplitude. The amplitude of the responses generally increases with time, probably because the distance between the tip of the micropipette and the soma–dendritic membrane grows smaller. Fig. 3 A, upper trace, shows

![Image of graph showing extracellular recording from a cell body. Components are separated by arrows. Monitoring pulses at end of sweeps. Lower traces, simultaneously recorded multicellular response. The strength of the orthodromic stimulus is greater in B than in A.](image)

the response after a threshold stimulus for the second component was applied to the contralateral optic nerve. The simultaneously recorded lower trace shows the multicellular response. Fig. 3 B, upper trace, shows the effect of a stronger stimulus, as can be seen from the lower trace of this figure. The records of Fig. 3 B were obtained 1 second after those of Fig. 3 A. The effect of changing the
strength of the stimulus was reversible. The upper traces are similar except for
the first component of the response, which appears earlier and rises to a higher
level. The reduced latency after the stronger stimulus may result from stimu-
lation of the optic nerve at a greater distance from the stimulating electrode
because of greater spread of the effective stimulating current. It seems probable
from the higher level of the first component in Fig. 3 B, as compared with Fig.
3 A, that the amplitude of the first component varies with the strength of the
stimulus, or is graded. The presence of grading is not certain because the

![Image of Figure 4]

amplitude of the responses varied with time. If grading is present, it is not a
continuous process. The absence of continuous grading differs from the excita-
tory synaptic activity on the motoneuron, as reported by Coombs, Eccles, and
Fatt (14). A similar lack of continuous gradation has been observed in some
inhibitory synaptic activity at the motoneuron by Coombs, Eccles, and Fatt
(15). The absence of continuous gradation will be discussed later.

Four sweeps occurring at 1 second intervals were superimposed to make the
record shown in Fig. 4. The stimulus was constant and at threshold for the
second component, as in Fig. 3 A. Two of the stimuli produced the second com-
ponent at the peak of the first, and one stimulus produced it during a plateau
at the peak of the first component. One of the stimuli of Fig. 4 evoked the first
component alone. There was considerable variation between cells in the time
course of the first component recorded alone, but a frequently occurring time
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course was like the one in Fig. 4. Its time course is similar to the synaptic current of the lateral geniculate that has been recorded with coarse electrodes by P. O. Bishop (5). Since the first component is the initial postsynaptic activity, is probably graded, and has a relatively long time course, it is likely that it is caused by an excitatory postsynaptic depolarization produced by synaptic activity. It may be noted in Fig. 3 B that this postsynaptic depolarization can begin within 0.5 msec. after the negative peak of the tract spike. As has been mentioned, a submaximal stimulus to the optic nerve, such as was employed in

Fig. 5. Upper trace, extracellular recording. Components are separated by arrows. Lower trace, simultaneously recorded multicellular response. Two equal orthodromic stimuli.

this study, excites only the largest group of fibers. Therefore, if the postsynaptic depolarization is caused by a transmitter substance, and if the synaptic endings are activated at the negative peak of the tract spike, the transmitter action can appear as a postsynaptic depolarization within 0.5 msec. after the arrival of the afferent volley.

The effect of a pair of equal stimuli is shown in Fig. 5. In the response to the second stimulus (upper trace), all the deflections after the first component are reduced in amplitude. The amplitude of the negative component varies directly with the size of the sum of the preceding second and third components. The first component is probably related to the strength of the stimulus, but the subsequent components are related to the interval between stimuli. The slowed conduction of the second tract spike (lower trace) probably is caused by relative refractoriness in afferent axons. The second response of Fig. 5, upper trace,
shows the second component appearing on the falling phase of the first. This is different from records of the synaptic potential across membranes in which the subsequent phases of activity can arise from the rising phase or peak of the potential, but not from the falling phase. An example of an intracellular record that shows the constancy of the threshold voltage can be seen in the report by Coombs, Curtis, and Eccles (12). The cause of this difference will be discussed later.

Fig. 6. Upper trace, extracellular recording. Components are separated by arrows. Monitoring pulse between shock artifact and responses. Lower trace, simultaneously recorded multicellular response. One orthodromic stimulus.

Fig. 6, upper trace, shows the response of soma-dendritic membrane that fired repetitively after a single stimulus. This figure shows that the various components of the response, other than the first, have the same properties that were shown in Fig. 5. The first, or synaptic, component of the second response is not discernible, and the amplitudes of all the subsequent components are reduced in comparison to those of the first response. The cause of repetitive firing in the lateral geniculate nucleus has been discussed by P. O. Bishop, Jeremy, and McLeod (7). A likely explanation for the long latency of the first, or synaptic, component of the first response is that the synaptic activation by
the afferent volley was not sufficient to fire the cell and that additional synaptic activation by the interneurons was necessary to provide threshold excitation. The synaptic activation may not have been sufficiently synchronous to cause a large first component in the first response or a visible component in the second response, or possibly the area of synaptic activation was so uniform that the flow of external current was minimal.

DISCUSSION

The First Component.—Evidence has been given that the first component of the extracellular potential recorded by the micropipette is dependent upon the synaptically initiated postsynaptic depolarization. In Fig. 3 it was shown that its amplitude probably increases with the strength of the stimulus, but it is not continuously graded. The grading may be a physiological confirmation of the anatomical study of the lateral geniculate nucleus of the cat by Glees (23) from which he was almost certain that one postsynaptic cell had synaptic contact with more than one presynaptic axon. This is in contrast to the suggestion of Glees and Le Gros Clark (24) that, in the monkey, each postsynaptic neuron is activated by only one presynaptic axon. The absence of continuous grading suggests that the number of presynaptic axons that have endings on one postsynaptic cell is limited to a few.

Since the first component is recorded extracellularly, it is produced by the flow of external current and should not be confused with the "excitatory postsynaptic potential" of Coombs et al. (14) which appears across the membrane. It may be that the first component is not recorded from the site of the major synaptic activity because it is a positive-going deflection, and Coombs et al. (14) have shown that excitatory synaptic activity depolarizes the somadendritic membrane. Extracellular current will flow from an area of lesser depolarization to one of greater depolarization. The statement of Glees (23) that synaptic contacts by fine terminal rings, the only kind of ending in the lateral geniculate, are more numerous on the dendrites than on the soma suggests a somatic location for the tip of the micropipette. It may be, however, that on the basis of chance some of the records were obtained from dendrites. If some were recorded from dendritic sites, they showed no differences from the usual records, and the dendritic membrane that the micropipette can encounter must have the same activity as the somatic membrane. The small first component of the first response in the upper trace of Fig. 6 suggests that the recording was from a point of medium synaptic depolarization on a dendrite. The anatomical boundary between the soma and the dendrite is vague, and the functional differences, if any, are more obscure. Therefore, the term "somadendritic membrane," which includes both, is employed here.

With respect to Fig. 5, it was noted that the second component could arise on the falling phase of the first component. This finding is in accord with the
hypothesis of the excitatory reactions in the motoneuron that has been proposed by Eccles (16) and Fuortes, Frank, and Becker (22), and others that are cited by Eccles (16). They believe that the soma-dendritic membrane has a high threshold and is not directly excited by synaptic depolarization. Before an action potential is initiated, the synaptic depolarization must spread electrotonically to the initial segment of the axon, which has a low threshold and is the trigger area. Since the tip of the micropipette is on soma–dendritic membrane and not on the trigger area, the second component may arise on any part of the first component. As will be shown, the time after the arrival of the afferent volley at which the second component appears will depend upon the spatial and temporal patterns of the synaptic activity and the electrical constants of the soma–dendritic membrane. The usual interval between the onset of the synaptic current and the subsequent activity is estimated at about 0.5 msec. From the drawings of O’Leary (28) it is estimated that the length of the dendrites is approximately 0.5 mm. If the electrotonic spread of a synaptic depolarization traverses this distance, the average velocity of a threshold depolarization is 1 mm./msec. This value is in the range of the values reported for dendrites in the cerebral cortex by Chang (10). His estimate is derived from the results of direct cortical stimulation, however, and the validity of estimates that are derived from this kind of data has been questioned by Purpura and Grundfest (31).

An attempt has been made to calculate the delay and attenuation that would effect a synaptic depolarization of the dendritic membrane if the spread of the depolarization were electrotonic. It was assumed that the structure conducting electrotonically is a smooth cylinder having a diameter of 5 μ. Values of 1000 ohm cm.² and 1 μF/cm.² were taken for the membrane resistance and capacity. Forty ohm cm. was chosen for the protoplasmic resistivity. These are the electrical constants of squid axons (11). If a unit impulse is applied at the end of a smooth, semi-infinite cylinder, the effect is given by Equation No. 5 in Table II of the tables of Fourier integrals by Campbell and Foster (8). The wave form at the source, shown in Fig. 7 A, was chosen for the applied voltage. It was divided into periods of 0.1 msec., and the average amplitude during each of these periods determined the size of each impulse. With the distance from the source held constant, the effect of each impulse was calculated. The total effect, as a function of time for a given distance, was obtained by summing the effects of the impulses. The results of these computations for a number of distances from the source are shown in Fig. 7 A.

If the assumptions made in the calculations can be applied to the dendrites in the lateral geniculate nucleus, it is seen in Fig. 7 A that the latency at a distance of 0.25 mm. from the source for a depolarization of 74 per cent of the maximum at the source is 0.25 msec. A 60 per cent depolarization would require the same time to appear at a distance of 0.5 mm. from the source. These values
for attenuation are reasonable. The latencies are short enough to make it seem possible that the spread of synaptic depolarization could be electrotonic in nature.\(^3\)

In order to illustrate how the second component can arise on the falling phase of the first component, let us assume that the trigger area fires at its peak depolarization and is 0.5 mm. away from the synaptic site, which is at the source in Fig. 7A. The membrane between them is passive. Let us assume further that the external potential, which corresponds to the first component recorded by the micropipette, is proportional to the potential difference between the source and a point 0.25 mm. away from it. Of course, the origin of the first

\(^3\) It may be of interest to compare Fig. 7A with the results of a similar calculation for a 0.5 \(\mu\) cylinder as shown in Fig. 7B. All the electrical constants are the same as those employed above except that 50 ohm cm. was chosen for the protoplasmic resistivity. The wave form in the inset was chosen for the applied voltage.
component is more complicated than the assumption made here. Since the potential difference between the source and the point 0.25 mm. away from it has already passed through its maximum by the time the point at 0.5 mm. reaches its threshold, the firing will occur on the falling phase of the first component.

The Second, Third, and Negative Components.—According to the hypothesis, cited above, that describes the excitatory reactions of motoneurons, the second component should be ascribed to the electrically excited initial segment of the axon. A depolarization at this site will draw current from the soma-dendritic membrane and the extracellular micropipette will record a positive deflection. It is after the second component that the hypothesis fails. The hypothesis states that all the soma-dendritic membrane becomes electrically excited and fires an impulse after the initial segment fires. In the records, however, it is

The term "electrical excitation” is used to designate the process of initiation of all-or-none, propagating, membrane activity that results from a depolarization caused
seen that the second component is followed by another positive deflection, the third component. If the soma–dendritic membrane generated an action potential, the second component should be followed by a negative component. The presence of the third component suggests that, after the second component, current is again drawn from electrically unexcited soma–dendritic membrane. The hypothesis can be altered to fit these results if it is assumed that only a small area of the soma–dendritic membrane is excited electrically. The area has to be small because a negative component never followed the second component. This suggests that the small, electrically excited area was not encountered by the micropipette.

Before further discussion, the sequence of events proposed here is shown schematically in Fig. 8. The tip of the micropipette, P, is close to electrically unexcited synaptic membrane. This kind of membrane is represented by the dotted line. Electrically excited membrane is represented by a solid line. The dots represent the terminal end rings of the afferent fibers. The first component of the extracellular flow of current is indicated by the arrow to flow from the less densely innervated proximal sections of dendrites to the more densely innervated dendritic ends. The second component flows toward the electrically excited initial segment of the axon. The third component flows toward the small area of electrically excited somatic membrane with a high threshold. This membrane may be a transitional sort between electrically excited and synaptically excited by anything, i.e., synaptic transmitter substances, applied electric currents, or mechanical deformation. If a membrane does not respond to a depolarization in this manner, it is considered to be “electrically unexcited” although it may depolarize in response to some stimuli.
membrane. Grundfest (26) has recently published a review that cites much
evidence pointing to the view that synaptically excited membranes are not
excited electrically. The somatic membrane of the principal cell of the lateral
geniculate nucleus (23), as well as that of the anterior horn cell, has many
synaptic endings.

If the hypothesis of the excitatory reactions is further modified so that the initial
segment of the axon alone is the site of all the electrically initiated activity, i.e.
both the second and third components, the interpretation of the responses reported
here would be essentially unchanged. The only difference is that the third component
of the somatic membrane current would then flow toward the initial segment instead
of to the soma.

Among the other schemes that might be proposed, one that deserves consideration
is that the third component of the external current flowing away from the soma-
dendritic membrane might go toward the recurrent collaterals. O'Leary (28) states
that "after emergence from the cell a typical axon issues a number of recurrent
collaterals...." It is probable that part of the third component is contributed by
the activity of the collaterals, but the evidence suggests that this contribution is
small. If it were large, it would be seen as a significant potential in the intracellular
recordings from antidromically activated motoneurons, and it is not (13).

It does not seem possible at present to record faithfully the normal membrane
voltage transients from geniculate cell bodies. Intracellular action potentials
have been recorded in the mammalian central nervous system by Eccles and
collaborators (16), Fuortes et al. (22), and Phillips (30). The records of these
investigators are much alike. A typical intracellular response to antidromic
stimulation recorded by Fuortes et al. (22) is shown in Fig. 9 A. The properties
of the components of this response are similar to those of the components of the
extracellular responses shown in Fig. 9 B. In their reduction after a conditioning
response, the second and third components are like the two components of the
rising phase of the action potential. This can be seen by comparing Fig. 1 of
the paper by Fuortes et al. (22) with Figs. 5 and 6 of this report. Such a corre-
spondence is required by the modified hypothesis.

The corrected record in Fig. 9 B has an appearance that suggests that it
might be related to the derivative of the voltage transient across soma-dendritic
membrane. This speculation is reasonable and can be tested if the major portion
of the soma-dendritic membrane is not excited electrically. It is possible to
calculate the flow of current across the somatic membrane if assumptions are
made about its electrical constants and its surface area. An estimate of 10⁻³ cm.²
has been suggested by Eccles (16) for the surface area of the motoneuron. Frank
and Fuortes (20) give values of 1.7 MΩ and 0.6 × 10⁻⁹ farads for the mem-
brane resistance and capacity of the motoneuron. The electrical constants of
somatic membrane are calculated as 1700 ohm cm.² and 0.6 µf./cm.² from these
data. These values are close to the electrical constants of squid axons (11) that
Fig. 9. A, intracellular recording of motoneuron action potential, antidromic activation (22). B, extracellular recording before (solid line) and after (dotted line) correction for frequency response of input probe. C, components of membrane current calculated from A. Capacitive component shown by solid line, conductive component by dotted line. D, sum of the two components in C.
are used in other calculations in this report. It is estimated that the diameter of
a principal cell in the lateral geniculate nucleus is 20 μ from plate 5 of the study
of Glees (23) and from 50 Nissl stained cells that were measured in this labora-
tory. The resistance and capacity across the wall of a sphere with a diameter of
20 μ are 135 MΩ and 7.6 pf. The total flow of current is the sum of the capaci-
tive component, which is the product of the derivative of the action potential
and the capacity of the membrane, and the conductive component which is the
action potential divided by the membrane resistance. The action potential
shown in Fig. 9 A was used for the calculation. For this calculation, it is as-
sumed that the rectifying properties of the membrane are negligible (13, 20).
The two components have been drawn in Fig. 9 C, and their sum is shown in
Fig. 9 D. The absolute magnitude of the two components depends upon the
effective surface area, which is the most questionable of the approximations and
might be too low. The relative magnitude of one component to the other and
the shape of their sum, however, are independent of the surface area and depend
upon the time constant of the soma–dendritic membrane. If the time constant
is really greater than 1.02 msec., which is close to the value given by Frank and
Fuortes (20), the ratio of capacitive to ohmic current will be greater. The
corrected record in Fig. 9 B and the computed curve in Fig. 9 D are reasonably
alike. The synaptic component of the current has been omitted in the calcula-
tion. K. Frank (personal communication) has obtained records from anti-
dromically excited motoneurons just before the appearance of the resting
potential. The records of Frank are very similar to Fig. 9 D. It seems likely
that the extracellular recordings are the change in voltage caused by the flow of
the membrane current across the external resistance between the tip of the mi-
cropipette and the zero potential surface, as defined by the indifferent elec-
trode. It is assumed that the zero potential surface does not move appreciably
with respect to the tip of the micropipette after the start of the second compo-
nent. This assumption is necessary in order to keep the external resistance con-
stant. In the hypothesis presented here, the site of the activity responsible for
the second and subsequent components of the records is located on a small area
of membrane relative to that of the whole soma–dendritic membrane. Since
the zero potential surface must pass through the junction between active
and inactive membrane, its position is relatively fixed. 4

4 Dr. Lorente de Nó, in A Study of Nerve Physiology, Studies from The Rockefeller
Institute for Medical Research, 1947, 132, chapter XVI, has noted the proportion-
ality between the membrane current and the extracellular potential near the surface
of neural structures in a volume conductor.
The amplitude of the corrected extracellular potential in Fig. 9 B is probably close
to 15 mv. It should be noted that this peak occurs during the rising phase of the
action potential across the membrane, and its amplitude does not indicate that the
peak of the action potential at the source need be greater than 100 mv.
Fatt (17) has described extracellular recordings from motoneurons. His recordings are roughly similar in time course to those presented here, but of opposite polarity, and lead to the view that the soma–dendritic membrane is electrically excited. The cause of the difference between the results of these two studies is not apparent. It may be related to the distance between the tip of the micropipette and the soma–dendritic membrane because it is probable that the records of Fatt were obtained at a greater distance than were the recordings in the present study. No recordings like those of Fatt were observed in this study, probably because they were lost in the noise. It is possible that the soma–dendritic membrane was rendered electrically inexcitable by pressure from the micropipette in this study, although such an effect has not been noted previously.

The second component of the intracellularly recorded action potential of the motoneuron is longer in duration than the axonal action potential, according to K. Frank (personal communication). His finding is in accord with the scheme proposed here because of the prolongation of the wave form that would result from an electrotonic spread from the source to the site of recording (Fig. 7). Fuortes et al. (22) have given evidence that the membrane which produces the second component of the intracellular recordings from motoneurons need not be electrically excited for a propagating impulse to occur in the axon. This component is the voltage that causes the third component of the flow of current away from the soma in the scheme shown in Fig. 8. The functional significance of this activity is not clear, but at present there is no evidence that the major portion of the soma–dendritic membrane is needed for any purpose other than to receive synaptic excitation.

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