ACCOMMODATION AND AUTORHYTHMIC MECHANISM IN SINGLE SENSORY FIBRES

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THE TECHNIQUE for measuring accommodation directly in relation to the discharge of impulses, developed in this laboratory by Skoglund (21), makes it possible to correlate a number of properties of nervous activity with the accommodation curves. The latter serve as reference point in the analysis which also by this method is shifting emphasis from measurements of threshold variations to inspection of the discharge as such and measurements of its properties. A further improvement upon Skoglund’s work is introduced in this paper by the use of micro-electrodes, placed directly on the sensory roots in order to isolate single fibres in nerves electrically stimulated with linearly rising currents. This technique is here used for the purpose of studying the properties of the autorhythemic mechanism in sensory fibres of different accommodative resistance.

Bernhard, Granit and Skoglund (6) proposed as a working hypothesis that the electrotonic potential, seen in spinal roots by Barron and Matthews (5) and studied in the optic nerve by Bernhard (7, 8, 9) serves as exciting for the autorhythmic mechanism in the nerve itself. From this and allied points of view we need more information about the properties of the rhythmic discharge caused by stimulation with slowly rising currents imitating possible generator potentials conducted electrotonically from the axon hillock down the fibres.

TECHNIQUE AND PROCEDURE

Stimulation. The stimulating device, built by the physicist of this laboratory, Mr. K. T. Helme, has been described in detail by Skoglund (21). The apparatus delivers linearly increasing currents of strictly controllable gradient and strength through the anode circuit of a valve. This stimulator is connected so as to shift the one beam of a double cathode ray in proportion to the rate of rise of the stimulating currents, the other beam being used for simultaneous records of the discharge in the nerve through a condenser coupled amplifier (see the figures of this paper). Strength and gradient are independent variables. The stimulus was driven up to a certain strength at a certain rate, then left at plateau height for some time, and finally allowed to drop back at a rate of fall corresponding to its rate of rise. If the plateaus were brief, the stimulator was operated iteratively by a sweep circuit. With longer plateaus it was necessary to start the stimulator manually. Plateaus from a few milliseconds to some 60 seconds were used.

Preparation. The spinal cord of decerebrate cats was laid bare and the animals slightly lifted up in the preparation box by a specially designed clamp gripping firmly around one thoracic and one sacral spinous process and rigidly fixed to a heavy stand. These precautions are necessary for the sake of the micro-electrode. Without a clamp on the vertebrae themselves each respiratory movement is accompanied by considerable excursions of the preparation under the electrode. Fine adjustment of the latter was achieved with the aid of a micromanipulator. Well chlorinated silver-silverchloride electrodes were used for stimulation. In order to differentiate between nerves from the cutaneous and the muscular end organs these electrodes were either placed on the saphenous nerve or on twigs from the
popliteal nerve where they enter the fleshy portion of the muscles below the knee. Sometimes the whole sciatic stem was used.

The micro-electrode was of the type used in this laboratory (14) for work on the retina and consisted of a fine platinum wire insulated by glass. It is pressed vertically against the dorsal roots not far from the point where they enter the cord. Some fibres are then found to be spontaneously active, others silent, some again are incited to activity by the pressure of the micro-electrode. Spontaneous discharges may or may not be accelerated by the stimulus. When relatively thin muscular branches are stimulated it is difficult to find an active fibre. It is also easier to locate a diffuse discharge in response to stimulation than to succeed in isolating a single spike. It is possible, in cases when a large spike suddenly turns up in perfect isolation, that it represents a certain amount of synchronized activity. Still, the discharges look and behave like so-called single units. Their often less strict correspondence with the all-or-none law can be explained by the influence of the discharge in adjacent elements.

A time signal interrupts the beam for marking the stimulus. Dependent upon what is being pictured this beam is interrupted at a rate of 50 or 500 per sec.

RESULTS

All-or-none nature of response. Only if several active fibres are lying under the electrode can the dorsal root reflex (16, 22), conducted centrifugally from the spinal cord, be a source of error. However, the latent period of this discharge is much longer than that of the direct centripetal volley. But, when the micro-electrode is used, the chance of finding a centrifugally conducting fibre is practically nil. It is difficult to isolate a directly excited single spike.

In Fig. 1 are illustrated the effects of a variation in (i) strength of stimulus at constant rate of rise and (ii) length of plateau at constant strength and rate of rise. In both cases the same stimulus pattern was swept several times across the screen of the tube. In none of the later pictures has this particular technical arrangement been used. Figure 1 is reproduced to show the all-or-none manner in which impulses are added up to a rhythmic discharge. With less perfect isolation the spikes diminish when strength or gradient is diminished. Both variations, in strength from a to d, and in plateau length from e to h, show that spikes are added with such regularity that the whole process can be swept across the tube several times without any other effect than a slight increase in width of the spikes, indicating minor variations of latent period. Our technique is thus sufficiently discriminative for the purpose for which we intend to use it.
Accommodations curve. In order to plot accommodation curves (21) the actual stimuli of different rates of rise are drawn in a co-ordinate system in which the abscissae accordingly are rising times and the ordinates strength. These values are obtained directly from the photographed curves (see figures) in which the final plateau level of current always was checked by a milliammeter in the circuit. Thus one does not merely rely on the amplified deflexion of the "stimulus-beam" of the cathode ray. With a large range of stimulus intensities tested, it is often necessary to alter the degree of amplification in order to keep the beam within the proportionality range of the instruments.

The various stimuli having been inserted into the co-ordinate system, the moment of appearance of the first spike is marked on the curve for each linearly rising stimulus. The points so obtained are joined to a curve (see Fig. 2) which accordingly illustrates the strength to which it has been neces-

\[ \frac{1}{I_0} \]

\[ \text{msec.} \]

FIG. 2. Average accommodation curve for muscular afferents (upper curve) and for the saphenous (lower curve). Ordinates multiples of rheobasic strength \( (I/I_0) \) (see text).

sary to drive the slowly rising current at each particular gradient in order to elicit one impulse, the first of a series, or a single spike if others do not follow. For rapidly rising stimuli the conduction time must be subtracted.

The graph so obtained is of the same type as the one introduced by von Kries (18) and also used by Hill (15) and his collaborators. Depending upon the particular problem in view, strength of current \( I \) may be given in milliamp. or in multiples of rheobasic strength \( (I/I_0) \). The inverse value of the rate of rise of the initial rectilinear portion of the curve corresponds to Hill's constant \( \lambda \). However, Skoglund's direct method of measuring accommodation and plotting the curve from photographed responses eliminates a number of errors and difficulties inherent in the methods based on observation of a threshold muscle contraction as "constant" index (6, 21) and makes it possible to isolate single fibres, not to mention the advantage of also being able to study sensory nerves by the direct method.

In Fig. 2 are plotted the average accommodation curves for muscular afferents and the purely cutaneous saphenous nerve (A fibres). The latter curve hardly rises at all above the rheobase. The muscular afferent also has relatively little accommodation, compared with motor nerves (12, 21). Breakdown of accommodation follows at about 1.5 rheobases. Hill's constant \( \lambda \) was about 150–200 msec. with muscular afferents and approaching infinity with the saphenous. These differences, as we shall see, are large enough to reappear mirrored in the properties of the autorhythmic mechanism of the nerves.
Two phases of rhythmic discharge. "Silent period." It has been pointed out previously (11, 21) that the rhythmic discharge can be divided into two phases, initial spikes of high frequency and a later prolonged discharge. We have now an opportunity of finding out whether these phases occur in a single element or represent different fibres. From this point of view Fig. 3 is of particular interest. The rate of rise is constant and the final strength of the current varies from a to f. Record g is from another experiment.

![Fig. 3. Muscular afferent. Stimuli rising from a to f at constant rate of rise to greater strength: a, 1.4 rheobases, b, 1.6, c, 2.0, d, 2.4, e, 3.2 and f, 4.0 rheobases. Record g from another experiment illustrates "silent period."](image)

![Fig. 4. Muscular afferent. Strength of stimulus increases from a to e (see text). The plateau frequencies are: a, 0, b, 75, c, 140, d, 275 and e, 450 per sec. These are counted after about 20 msec. of stimulation. Time in 50/sec.](image)

The development of the initial phase of the discharge is seen in the records a to d. Continuation of the rising phase of the current is accompanied by the birth of new impulses. In record d, however, there follows after a silent period the first impulse of the later plateau-phase of the discharge. Still stronger stimuli, as in e and f, do not lead to a silent period because the threshold for the plateau-phase is then reached during or just after the rising portion of the stimulus so that it becomes submerged into the initial phase. With linearly rising stimuli the occurrence of a silent period between the two phases of the discharge is left to chance but it could, no doubt, be produced regularly if with our apparatus it were possible to decrease the rate of rise of the stimulus somewhat at the top. In record g the silent period is very prominent.
Previously we (6) have defined as "breakdown of accommodation" the fact that at a certain strength of current its strength alone rather than its rate of rise becomes significant (see Fig. 2) and pointed out that this intensity region is recognized by the flattening of the accommodation curve accompanied by iterative firing. The plateau discharge belongs to this late portion of the accommodation curve. Consequently this is the most important phase of the autorhythmic mechanism in sensory nerves which have low accommodative resistance. In the saphenous nerve it sets in practically as soon as the current has risen a little above rheobasic strength; in muscular afferents there is already a definite initial phase. But on the whole our preparation is more suitable for studying the plateau-phase. Motor nerve should be used for the initial phase. Gradient is there relatively more important.

In sensory nerves the initial phase seems to share with the plateau-phase the property of being more dependent upon current strength than upon its gradient. The range of variation in the frequency of the discharge is far greater during the plateau-phase than in the initial phase.

Plateau discharge and current strength. It is known that in general the frequency of the repetitive discharge is greater for stronger stimuli (12, 13, 17, 21). In Fig. 4 is illustrated the effect of current strength on a single muscular afferent with $\lambda = 200$. On account of the large intensity range it has been necessary to use different degrees of amplification of the stimulus-beam of the cathode ray so that the deflexions are not proportional to current strength. In a, at 2.1 rheobases, there is merely the initial phase, in b, at 3.9 rheobases, the plateau-phase is well developed. In c the strength is 5.8 rheobases. The initial phase is from the very first record activated at a frequency high enough to cause diminution of the size of spikes. In d, at 9.7 rheobases, the plateau-phase is activated at a frequency leading to a relatively extended depression of spike size, and in e, at 15.0 rheobases, the spikes are subnormal for the whole period illustrated. The maximal frequency is at about 450 per sec.

In Fig. 5 the quantitative relation between spike frequency and current strength in multiples of rheobasic strength ($I/I_0$) is illustrated. In the inset the abscissae are log frequency and the strength-frequency relation has been compared for a muscular afferent and a saphenous. The difference between these two curves does not exceed the range of variation in different experiments. The asymptote of the curves is found to begin in the frequency re-
gion 400–500. We conclude that variations in accommodative resistance within the limits of these experiments have no definite influence on the strength-frequency relation.

*Adaptation and accommodation.* By adaptation is meant the fact that the frequency of the discharge gradually sinks during prolonged stimulation at plateau height. Figure 6 illustrates different stages of this process during the course of stimulation with a current 5.8 times the rheobase. This nerve is a muscular afferent. With the saphenous we have often kept the stimulus at plateau height for 60 sec. and still seen a discharge of considerable frequency. But in nerves with some accommodation the frequency much sooner

![Fig. 6. Muscular afferent. The course of adaptation to plateau strength of a stimulus 5.8 times the rheobase. Record begins in a with about 250 impulses per sec. In b, after 2.5 sec., it has fallen to 35/sec., in c, after 5.0 sec., to 18/sec.](image)

reaches zero. In such cases the total adaptation time (T) can be measured.

A set of curves illustrating the decline in frequency from different levels of excitation (I/I₀), defined by the initial plateau frequencies, is found in Fig. 7. The abscissae show the duration of the plateau stimulus. The nerve is a muscular afferent. In the inset of Fig. 7 multiples of rheobasic strength (I/I₀) are plotted against the logarithm of the total adaptation time (log T), i.e. the time from the first to the last impulse of the discharge caused by

![Fig. 7. Muscular afferent. Course of adaptation for stimuli of different strength in terms of frequency of discharge as ordinates against duration of stimulation as abscissae. Inset. Comparison of a muscular afferent (filled circles) of λ = 200 with a saphenous (open circles) of λ = ∞ with respect to the total adaptation time T for the rhythmic discharge at strengths of stimulation given as ordinates in multiples of the rheobase. Log T on the abscissa. Stimulation has been continued until the rhythmic discharge has stopped.](image)
a certain stimulus. Here, as in all our experiments, the total adaptation time is a function of the accommodative resistance. The steeper the rise of the accommodation curve, the steeper also the rise of the curve in the $I/I_0 - \log T$ graph, the shorter consequently the adaptation time for a given multiple of rheobasic strength.

This difference is well brought out in the inset of Fig. 7 by the comparison of the muscular afferent of $\lambda = 200$ with the saphenous of a $\lambda$ approaching infinity. It is further emphasized by an interesting experiment in which the accommodation gradually rose while we succeeded in keeping the same fibre for several hours under the micro-electrode. Hill's constant $\lambda$ was about 200

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig8.png}
\caption{Accommodation curves for a muscular afferent in the beginning (filled circles) and at the end (open circles) of an experiment (see text). Inset: Plot of $\log T$ (abscissae) against multiples of rheobasic strength (ordinates) as in inset of Fig. 7. Curve to the left thus belongs to nerve giving late accommodation curve ($\lambda = 85$), curve to the right to nerve giving early accommodation curve ($\lambda = 200$).}
\end{figure}

in the beginning of the experiment and around 85 some hours later. The two accommodation curves from which these approximated constants were obtained (from the early portion of the curve, as always) are shown in Fig. 8. In the inset of the same figure are plotted the logarithms of the total adaptation times ($\log T$), just as in the inset of Fig. 7. The plot shows that the shortening of the adaptation time and the consequent steeper rise and shift of the $I/I_0 - \log T$ curve actually is a function of the accommodative resistance of the active fibre and not due to differences in structure between muscular afferents and the saphenous, of a character unconnected with accommodation. Both curves here refer to the same single muscular afferent fibre in different states of accommodation.

\textit{Adaptation and cathodal depression}. Turning now to the original record of the experiment, evaluated above in Fig. 8, we find in Fig. 9 the late stage of it, characterized by $\lambda = 85$, which should be compared with the records in Fig. 6 from the early stage ($\lambda = 200$). In Fig. 6, at 5.8 rheobases, there was still a plateau discharge present 5.0 sec. after initiation of the rhythmic activity. In record b of Fig. 9, at 6.0 rheobases, the discharge stops after a little over half a second. It does not last very much longer when the strength is increased in c to 9.0 rheobases. The reason for this becomes evident when the current is further increased, to 14 rheobases in d. The whole plateau discharge is now inhibited and possibly also the last portion of the initial phase. This is the cathodal depression, noted by Schiff (20), then seen
by several others, and well analyzed by Werigo (23). It is often nowadays (17, 19) called Werigo's cathodal depression. This block is a decisive factor in "adaptation" and probably determines adaptation time (log T) at all strengths of current, though visible as a complete inhibition of the discharge only at higher levels of stimulation intensity, provided that the accommodative resistance is sufficiently high. In nerves with little accommodation the cathodal depression must be weakly developed or so late as to have fallen outside our longest observation times (around a minute). With motor nerves Skoglund (as yet unpublished work) finds it regularly and has been studying the phenomenon in this laboratory. Its connexion with accommodation is shown by the fact that it here also turns up in a sensory nerve as soon as accommodation has risen a little above the commonly obtained values. In Fig. 4, record e, there was no cathodal depression even at 15.0 rheobases.

"Intermittent conduction." In studying the centrifugal discharge through the dorsal roots in response to adequate stimulation of different afferents Barron and Matthews (4) noted that it sometimes was split up into intermittent groups of impulses. Such intermittency was held by them to be due to temporary blockage in the spinal cord, caused by cord potentials conducted electrotonically to some critical point in the passage of the excitatory disturbance. However, in our experience a similar phenomenon is found also in peripheral sensory nerves.

Intermittent spontaneous discharges of great regularity are seen every now and then with an afferent root under the micro-electrode. The source of these spontaneous intermittent discharges is the cut end of the nerve. They disappear if a drop of a cocaine solution is applied onto the severed region of the afferent nerve and thus belong to the "grouped injury discharges" described by Adrian (2). But there are also cases in which the nerve is silent and reacts to the plateau stimulus with an intermittent discharge.
The activation of such a dormant tendency to intermittent conduction is shown in Fig. 10. The stimulus seems to facilitate a process on the verge of activity. Similar observations have been reported by Erlanger and Blair (11). Barron and Matthews have emphasized the significance of their own observations for central inhibition. Like most central phenomena, this also seems to have its peripheral counterpart. Barron and Matthews’ explanation could be adapted to fit our case but there is little reason to theorize here about observations which have been wholly unsystematical.

**DISCUSSION**

*Adaptation time, accommodation and cathodal depression.* Hill’s theory (15) explains the occurrence of rhythmic discharges to constant currents by the assumption that the “local potential” $V$ for a certain time $T$ remains above the “threshold” $U$. In the words of Katz (17): “during a certain time $T$, therefore, $V$ will be greater than $U$, and throughout this time repetitive response might be expected to occur, at intervals determined by the refractory period.” Stronger stimuli increase the frequency by eliciting impulses earlier in the refractory period.

The relation between this time $T$ (which here has been called total adaptation time), the constant $\lambda$, and stimulus strength $I/I_0$ has also been given by Katz. It is $T = \lambda \log e I/I_0$. In frogs (whole nerve) he finds good agreement between experiment and theory. The reason for this may be the limited range of intensities tested. It is immediately seen that in our experiments with a value for $\lambda$ around 200 msec. $T$ may be of the order of 1000 msec., for $I/I_0$ around 3–4. The formula does not therefore fit our case. It may nevertheless be of some interest to compare the curves for the sensory fibre (Figs. 8 and 9) in which $\lambda$ was 200 in the beginning and 85 at the end of the experiment. Calling the adaptation times $T_{200}$ and $T_{85}$ for $\lambda_1 = 200$ and $\lambda_2 = 85$, it is clear that on the theory

$$T_{200} - T_{85} = \log e \frac{I}{I_0} (\lambda_1 - \lambda_2),$$

the difference between the two constants being 115.

The right and left members of this equation are compared in Table 1 for different values of $I/I_0$.

<table>
<thead>
<tr>
<th>$I/I_0$</th>
<th>$115 \log e I/I_0$</th>
<th>$T_{200} - T_{85}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>262</td>
<td>38.000</td>
</tr>
<tr>
<td>6</td>
<td>206</td>
<td>4.400</td>
</tr>
<tr>
<td>4</td>
<td>160</td>
<td>1.500</td>
</tr>
<tr>
<td>2 extrapolated</td>
<td>79</td>
<td>0.230</td>
</tr>
</tbody>
</table>

*Fig. 10. “Intermittent conduction.”* Stimulation of muscular afferent elicits discharge which soon is split up into regular groups.
The total adaptation time is thus of an order of magnitude which suggests, by decreasing with $I/I_0$, that quantitative agreement with the theory in sensory nerves only can be expected below the double rheobase. Nevertheless the theory has been a valuable instrument in the experimental analysis.

However, accommodation appears in an important function as common denominator for the general resistance of the nerve to impulse production. The greater this resistance, the more developed the cathodal depression, and the shorter the adaptation time which probably, as stated, is determined by the development of the Schiff-Werigo inhibition. This is an instance of what is meant by our statement in the introduction that accommodation serves as reference point in the analysis.

Whether this late cathodal depression can be equated with the early cathodal depression, studied by Erlanger and Blair (10, 12), remains to be found out in work with motor nerve where accommodative resistance is very much better developed. But it is clearly important that in their work too, accommodation, the early cathodal depression and the degree of repetitiousness are connected in the manner in which they now appear connected here (cf. also 21) despite the different mode of attack. Early cathodal depression is synonymous with accommodation as measured by Erlanger and Blair by a method based on testing the cathodal excitability with a shock technique.

Autorhythmic discharge. The fact that the sensory nerves, which are activated individually by isolated peripheral structures with limited energy resources, possess little accommodative resistance by comparison with motor nerves (12, 21) is in agreement with our hypothesis that the autorhythmic mechanism of these nerves can be put into operation by generator potentials carried down electrotonically along the nerve in simple end organs probably by direct chemical excitation of the nerve fibre. From this point of view it is interesting that particularly low accommodation and little adaptation is found in a cutaneous nerve such as the saphenous in which, on the theory, the autorhythmic mechanism would be started by energy released by such weak stimuli as touch or the bending of a hair. However, the degree of adaptation is clearly determined by the end organ and not by the mechanism in the nerve, as directly demonstrated by Adrian, Cattell and Hoagland (3) for cutaneous organs. In the nerve, adaptation of the autorhythmic mechanism is less marked in the saphenous, and clearly noticeable in the muscular afferents whereas the adaptabilities of the corresponding end organs are the other way round (1).

The fact that "gradient" is of relatively little significance in sensory nerves but highly important for many sense organs would seem to throw some light on the differentiation of such sense organs into a primary apparatus for picking up the energy of the adequate stimulus and a secondary generator mechanism firing the nerve. Sufficiently strong stimuli may, however, cause a "gradient" also in the generator mechanism and lead to a discharge interrupted by a "silent period" (initial phase followed by plateau phase).
ACCOMMODATION AND AUTORHYTHMIC MECHANISM 347

Considering the difference in accommodation between motor and sensory nerves it is clear that in reflex activity the transition from the one system to the other suggests interesting possibilities for selection on the basis of differences in accommodative resistance in the internuncial and output channels of the central nervous system.

SUMMARY

The repetitive discharge in response to slowly rising linear stimuli has been recorded with the aid of micro-electrodes from cutaneous and muscular afferents. Single fibres could be isolated by placing the micro-electrode on the dorsal roots. Stimulus form and nerve response are pictured simultaneously with the aid of a double cathode ray oscillograph on the same film.

By this method it is possible to measure the sensory accommodation curves directly and at the same time correlate them with the properties of the iterative discharge.

There is little if any accommodation in n. saphenous, representing cutaneous afferents (Hill’s constant \( \lambda \) approaching infinity). For different muscular twigs of n. popliteus the values for \( \lambda \) range from 150 to 200 msec.

The autorhythmic discharge caused by the slowly rising stimuli consists of an initial phase during the time the stimulus rises and a later plateau phase when the stimulus has reached a certain plateau level of strength. These two phases may be separated by a “silent period.”

The plateau discharge is characterized by a frequency which increases with stimulus strength. The strength-frequency curve for single fibres is illustrated in Fig. 5. It is independent of the accommodative resistance of the nerve.

The total adaptation time (from first to last impulse) of the plateau discharge is a function of accommodation and of stimulus strength and decreases when the accommodative resistance increases or stimulus strength decreases. These relations are illustrated quantitatively for nerves of different accommodation in Fig. 7 and 8.

Strong stimuli continued on plateau height inhibit the discharge (Schiff-Werigo’s cathodal depression), provided that the nerves possess good accommodative resistance. It is suggested that the total adaptation time is largely determined by this factor.

The slowly rising stimulus sometimes causes a rhythmically grouped discharge instead of a continuous flow of impulses.

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REFERENCES


