

## MONOSYNAPTIC REFLEX RESPONSES OF INDIVIDUAL MOTONEURONS

By DAVID P. C. LLOYD AND A. K. McINTYRE

*(From the Laboratories of The Rockefeller Institute for Medical Research, New York,  
and the Department of Physiology, University of Otago,  
Dunedin, New Zealand)*

(Received for publication, March 2, 1955)

From time to time since the pioneering investigations of Adrian and Bronk (1) and of Denny-Brown (6), the techniques of unitary analysis have been applied to the study of reflex activity. The earlier techniques involved the cutting through of a nerve until a single responding motor axon remained, or the plunging of a concentric needle electrode into muscle from which unitary responses could be led. Identification of the responding motoneurons was automatic by virtue of recording electrode location. Longitudinal splitting of distally severed ventral roots is a simpler procedure and with a number of fine strands available a reasonable harvest of isolated motoneuron responses can be obtained from a single preparation. However, it was not until the autochthonous character of monosynaptic reflexes was established (15, 16) that motoneuron response recorded in a ventral root could be identified with the muscle mass to which it is directed. A number of workers have taken advantage of this finding to advance the study of single motoneuron responses (2, 8-10).

Recently another technique (13, 21) has been exploited, that involving impalement of motoneurons within the spinal cord by microelectrodes. Identification of an impaled motoneuron depends upon the same criteria that serve to identify motoneuron response in ventral root filaments. Each of these two newer methods has its advantages. Despite considerable uncertainty about many of the internally recorded potentials of motoneuron somata some interesting responses have been encountered that would not be revealed by ventral root recording. Nevertheless, for many purposes internal recording presents no advantage over ventral root recording, but rather disadvantage. Among such purposes are those of the present study, which include the development of a useful means for describing the monosynaptic reflex behavior of a "synthetic" motoneuron pool in terms of observed behavior in a number of individuals and the testing of resemblance between the behavior of the synthetic pool and that of a "natural" pool. In this way it is hoped that a foundation can be laid for assessing the degree of significance to be accorded any particular form of individual behavior that may be encountered in future experimentation.

This study is concerned with monosynaptic reflex responses of individual motoneurons of triceps surae in decapitate cat preparations. The medial and lateral gastrocnemius nerves were isolated, distally severed, and arranged for stimulation. Appropriate ventral roots were distally severed and drawn out on a dark plate upon which they were split initially into natural bundles each of which was then further split as circumstances dictated. In many experiments the brachial plexus was prepared for stimulation to provide a descending long spinal reflex excitatory background (14, 19).

As each ventral root strand was placed upon recording electrodes it was examined for content of triceps surae motoneurons by observing monosynaptic response, if present, to the strongest available synaptic drive: that provided by supramaximal group I afferent volleys elicited synchronously in both gastrocnemius nerves during a period of post-tetanic potentiation and anteceded by some 12 msec., in a number of experiments, by stimulation of the brachial plexus. If more than one motoneuron responded in the monosynaptic reflex tempo the strand was further subdivided and the test repeated. Upon finding an apparently single unit response synaptic drive was reduced progressively by omitting the brachial plexus stimulation, the tetanization of the gastrocnemius nerves, stimulation of one or the other gastrocnemius nerve, and finally by reducing shock strength of stimulation applied to the remaining gastrocnemius nerve. It was a requirement before proceeding that the response disappear and return in an all-or-nothing fashion.

If no response appeared upon repeated testing at the highest level of synaptic drive it was assumed that the strand being tested was lacking in viable motor axons to triceps. To the extent that some motoneurons might conceivably be so deep in the subliminal fringe of monosynaptic connection as not to respond in the drastic circumstances provided that assumption would have been invalid. Obviously such neurons, if such there be, do not lend themselves to study. Occasionally, by virtue of slight but reasonably consistent difference in latency of response and significant difference in amplitude, it is possible to study the responses of more than one motoneuron simultaneously if subdivision by chance has left two viable gastrocnemius axons in the strand under observation.

Preliminary procedures having been completed, each individual tricipital motoneuron was subjected as circumstances dictated to many or all of the following varieties of synaptic drive:

1. Medial gastrocnemius alone.
2. Lateral gastrocnemius alone.
3. Medial and lateral gastrocnemius synchronized.
4. Medial gastrocnemius potentiated by tetanization.
5. Lateral gastrocnemius potentiated by tetanization.
6. Medial and lateral gastrocnemius synchronized and potentiated by tetanization.
7. Lateral gastrocnemius leading medial gastrocnemius by *ca.* 1 msec. both potentiated by tetanization.

8. Medial gastrocnemius leading lateral gastrocnemius by *ca.* 1 msec. both potentiated by tetanization.
- 9-16. Each of the foregoing varieties of input anteceded by stimulation of the brachial plexus.

In the present study supramaximal stimulation only has been employed, there having been no attempt made to examine the influence of gradation by strength of afferent stimulation, which latter has been studied in detail by Hunt (12). Stimuli, singly or in whatever chosen combination, were delivered rhythmically at a frequency of 25 per minute, sweep synchronized, each sweep (observed or photographed) for a period of time being recorded as displaying or not displaying a monosynaptically timed response.

In the several steady state conditions studied the performance of a motoneuron can be expressed by means of a *firing index* ( $Fi$ ) which is given by:

$$\frac{\text{No. responses}}{\text{No. trials}} \times 100$$

The attempt to give an expression to performance during the period of post-tetanic potentiation, which is not steady state, presents difficulties. Granit and Ström (8) have applied their probability method (which resembles except for the number of trials in each situation the firing index method here used) to non-steady state conditions. This is practical only if the change in state under investigation is relatively brief and if one is to be satisfied with a few trials at each test interval. Since each cycle of post-tetanic potentiation requires minutes for its completion (17) and for each test situation usually some 40 trials as a minimum are required, it would be fruitless effort to attempt the description of post-tetanic behavior according to firing indices as defined. A not altogether satisfactory substitute herein employed has been to determine the number of responses elicited in standard conditions of tetanization and low frequency rhythmic testing during the first post-tetanic minute, the result being expressed by:

$$\frac{\text{No. responses elicited}}{25} \times 100$$

25 being the possible maximum of responses at the standard test frequency employed.

*Graphical Representation of Monosynaptic Reflex Behavior in a Synthetic Motoneuron Pool.*—In all 110 tricipital motoneurons have been studied in the manner indicated. Of these 54 pertained to the medial head of gastrocnemius, the rest to lateral gastrocnemius, and soleus. These neurons may be considered collectively as constituting a synthetic tricipital motoneuron pool. To represent the monosynaptic reflex behavior of such a pool in a given circumstance of stimulation a plot is constructed in which the individual motoneurons are ranked in order of decreasing firing indices in that particular circumstance.

Fig. 1 contains two such plots representing behavior of the synthetic pool in two circumstances of stimulation. For present purpose no distinction is made between medial and lateral motoneurons. In each circumstance of stimulation it is seen that some motoneurons responded to every test stimulation ( $F_i =$

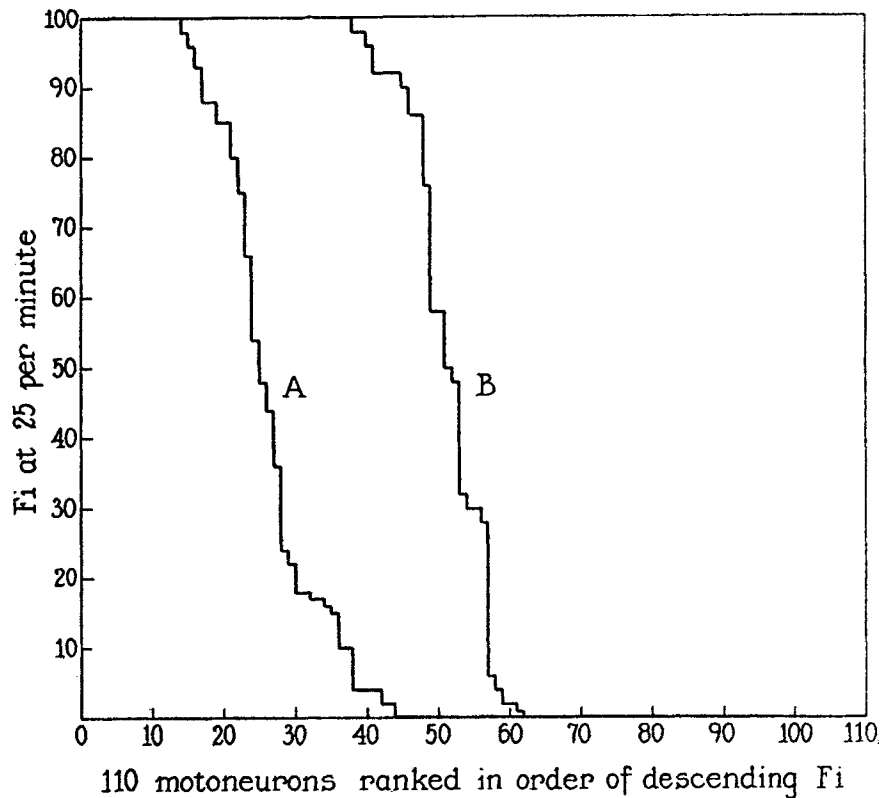


FIG. 1. The 110 motoneurons studied are here ranked in order of decreasing firing indices in response to standard maximal homonymous afferent volleys (A) and to standard maximal afferent volleys in the entire afferent supply of the synergic unit, triceps surae (B).

100), some did not respond to any test ( $F_i = 0$ ), and some responded in an intermediate percentage of the trials ( $F_i < 100$  and  $> 0$ ).

To reconstruct the fictitious monosynaptic reflex response of the synthetic pool one can regard the number of motoneurons yielding  $F_i = 100$  as representing the minimum discharge zone, the number of those yielding intermediate  $F_i$  values as representing the maximum variation in discharge zone, and the number of these yielding  $F_i = 0$  as the subliminal fringe complementary to the

discharge zone at its maximum. In the study of monosynaptic reflex responses of natural motoneuron pools one deals with variability of response by finding the average amplitude of a large number of responses elicited in identical conditions. In the synthetic pool the average discharge zone is given by

$$\frac{\sum_{F_i=1}^{100} f(F_i)}{100}$$

Average subliminal fringe is given by the remainder.

The plots of Fig. 1 represent the monosynaptic reflex behavior of 110 tricipital motoneurons when driven by one of the nerves to gastrocnemius (A) and when driven by the two gastrocnemius nerves synchronously activated (B). The single gastrocnemius nerve stimulated to obtain the results in curve A was in each case that homonymous with the motoneuron under study.

When driven by a fraction of the monosynaptic reflex input (medial or lateral gastrocnemius as occasion demanded) the synthetic pool of 110 motoneurons was found to contain a minimum discharge zone of 14, a maximum of 44. By calculation the average fictitious monosynaptic reflex response would be 26 and would occupy 23.6 per cent of the population. The shift from curve A to curve B describes the facilitatory influence of synchronously convergent heteronymous volleys. Minimum discharge zone has grown to 38, the maximum to 62, and calculated average fictitious monosynaptic reflex response to 53.5, or 48.6 per cent of the population.

Sixty-two of the present collection of motoneurons were studied at three levels of synaptic drive. Fig. 2 represents, in the manner of Fig. 1, the  $F_i$  behavior of these 62 motoneurons when driven by their homonymous monosynaptic input (curve A), by the entire monosynaptic input (curve B), and by the latter incident upon long spinal reflex background (curve C).

*Identification of Neurons.*—As a preliminary guide to the identification of individual motoneuron axons in ventral root filaments one can rely upon the expectation that lateral gastrocnemius motoneurons are the more numerous in the seventh lumbar ventral root, whereas medial gastrocnemius motoneurons are more numerous in the first sacral ventral root. Actually identification of motoneurons occupying any part of the maximal discharge zone in response to afferent volleys in one or the other gastrocnemius nerve is simple; identification of motoneurons in the minimal subliminal fringe sometimes is not. Table I is presented to illustrate in a general way the experimental procedure that has been followed and some individual results selected not to be representative, but rather to illustrate problems in identification. By “facilitated” in the table one has reference to responses obtained upon a background of long spinal reflex activity. Neuron 98 is immediately identifiable by its response at  $F_i = 18$  to stimulation of the lateral gastrocnemius nerve. Neuron 66 responded to stimula-

tion of the entire gastrocnemius nerve ( $Fi = 6$ ) but could be identified only with the aid of long spinal reflex background, or by dint of prior tetanization which brought it, in combination with medial gastrocnemius nerve stimulation, to  $Fi = 54$  and  $Fi = 92$  respectively. Neuron 60 would have been unidentifiable

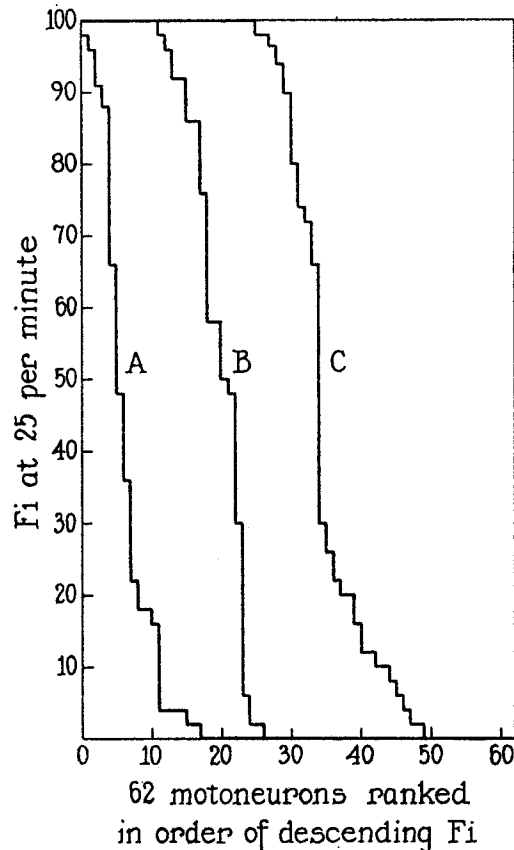


FIG. 2. As Fig. 1 but for 62 motoneurons that were studied at three levels of input: A, standard maximal homonymous input; B, standard maximal entire input; and C, maximal entire input on long spinal reflex background.

without the aid of prior tetanization, long spinal reflex facilitation alone being ineffective. Neuron 88 on the contrary required the long spinal influence for identification and, indeed, would not have been encountered without the use of brachial plexus stimulation in conjunction with monosynaptic reflex afferent volleys. It is worth noting, however, that neuron 88 is the only individual in the entire group that would have been missed entirely without long spinal reflex background. Neuron 57 could be identified without the long spinal influence,

but only when both gastrocnemius nerves were tetanized and subsequently stimulated with shocks separated in time by 1 msec. When, in the post-tetanic period, lateral gastrocnemius afferent volleys anteceded medial gastrocnemius afferent volleys no response ensued, but in the reverse sequence the neuron responded at  $Fi = 32$ , and in monosynaptic temporal relation to the lateral gastrocnemius afferent volleys, to establish its identity. With the aid of long spinal reflex background neuron 57 would have been found ( $Fi = 4$ ) without prior tetanization, but not identified. However, in conjunction with stimulation

TABLE I  
*Firing Indices of Motoneurons in Response to Various Afferent Inputs*

| No. | Status      | Normal |         |      | Post-tetanicly potentiated |         |      |       |       |
|-----|-------------|--------|---------|------|----------------------------|---------|------|-------|-------|
|     |             | Medial | Lateral | Both | Medial                     | Lateral | Both | L → M | M → L |
| 98  | Resting     | 0      | 18      | 92   | 0                          | 96      | 100  |       |       |
|     | Facilitated | 0      | 100     | 100  | 0                          | 100     | 100  |       |       |
| 66  | Resting     | 0      | 0       | 6    | 92                         | 0       | 100  |       |       |
|     | Facilitated | 54     | 0       | 100  | 100                        | 0       | 100  |       |       |
| 60  | Resting     | 0      | 0       | 0    | 8                          | 0       | 44   | 36    | 0     |
|     | Facilitated | 0      | 0       | 2    | 58                         | 0       | 88   | 88    | 0     |
| 88  | Resting     | 0      | 0       | 0    | 0                          | 0       | 0    |       |       |
|     | Facilitated | 0      | 14      | 66   | 0                          | 92      | 100  |       |       |
| 57  | Resting     | 0      | 0       | 0    | 0                          | 0       | 56   | 0     | 32    |
|     | Facilitated | 0      | 0       | 4    | 0                          | 40      | 92   |       |       |
| 58  | Resting     | 0      | 0       | 0    | 0                          | 0       | 32   | 0     | 0     |
|     | Facilitated | 0      | 0       | 0    | 0                          | 16      | 76   | 0     | 60    |
| 52  | Resting     | 0      | 0       | 0    | 0                          | 0       | 4    | 0     | 0     |
|     | Facilitated | 0      | 0       | 0    | 0                          | 0       | 56   | 0     | 8     |

of the lateral gastrocnemius nerve alone in the post-tetanic period  $Fi$  was brought to 40 which served for identification.

Neuron 58 could not have been found without prior tetanization of the entire gastrocnemius nerve ( $Fi = 32$ ) or prior tetanization of the lateral branch in concert with long spinal convergence, and could only be identified in the latter circumstance ( $Fi = 16$ ). Neuron 52 is of interest for it was only at the last step in the sequence of tests that identity could be established: that in which medial and lateral gastrocnemius afferent volleys fell in sequence both delivered in the post-tetanic state upon long spinal convergent background, and at that  $Fi$  was only 8.

It should be noted that every motoneuron examined provided evidence for excitatory connection from both homonymous and heteronymous afferent fibers.

*Considerations Relative to Intermediate Firing Indices.*—The end result (discharge or no discharge) of impingement upon a given motoneuron of a given monosynaptic reflex afferent volley is determined by the instantaneous excitability level of the motoneuron and the effective intensity of the impinging action. Were there no excitability fluctuation in the system firing indices could have no value other than 100 or zero. As it is, for each input tested some 20 to 30 per cent of the pool displayed intermediate  $F_i$  values.

With monosynaptic reflex afferent drive held constant at some value the presence of virtually every degree of intermediacy in firing index implies either that mean intrinsic responsivity of individual motoneurons varies widely throughout the pool, or that transmitter potentiality for the path stimulated is widely variant at the monosynaptic junctions to individual motoneurons of the pool. If mean motoneuron responsivity variation in the pool were the important factor individual motoneuron performances to different sorts of input should vary in like manner. In the one situation so far explored (20) this has proved not to be the case. This is in favor of the supposition that the range of firing indices reflects variation in transmitter potentialities. Thus it can be said that for a given input some 20 to 30 per cent of the junctions are active in a critical range of transmitter potentialities that allows fluctuation in the system to permit or prevent response.

Three sources of fluctuation may be considered: Spontaneous quantal variation of the sort discussed by Fatt and Katz, and Castillo and Katz (7, 3-5) in relation to end-plate potentials; intrinsic fluctuation of motoneuron responsivity; and variation in convergent "background" activity. Variations due to the first two mentioned causes should be random, or uncorrelated, and would tend to cancel in pool responses. Variation due to background activity should be highly correlated. Observation of pool responses (11) indicates that much of the variation in monosynaptic reflexes is correlated. Actually, however, as long as one is concerned strictly with the responses of individuals it makes no difference what the degree of correlation in fluctuation might be.

As synaptic drive is increased from some starting level, such as is provided by stimulation applied to one of the two gastrocnemius nerves, neurons move from the intermediate zone to the zone of occlusion ( $F_i = 100$ ) whilst others move into the intermediate zone from the subliminal zone. If a major stepwise increase is made, like that brought about by stimulating the entire tricipital afferent supply rather than a single branch, the intermediate zone comes to represent an almost completely different segment of the neuron population (Fig. 1). A further major shift of the intermediate zone occurs if long spinal reflex drive is added to gastrocnemius afferent input (Fig. 2). It is, however, of



interest and illustrative of an extreme condition that two neurons (59 and 102) remained within the intermediate zone at all three levels of drive, having  $Fi$  values of 2-58-98 and of 4-86-90 respectively.

Fig. 3 gives the frequency distribution of intermediate  $Fi$  values, the class interval being 10  $Fi$  on a "less than" basis. For present purpose all observed values of 0 and 100 are eliminated from consideration and the intermediate

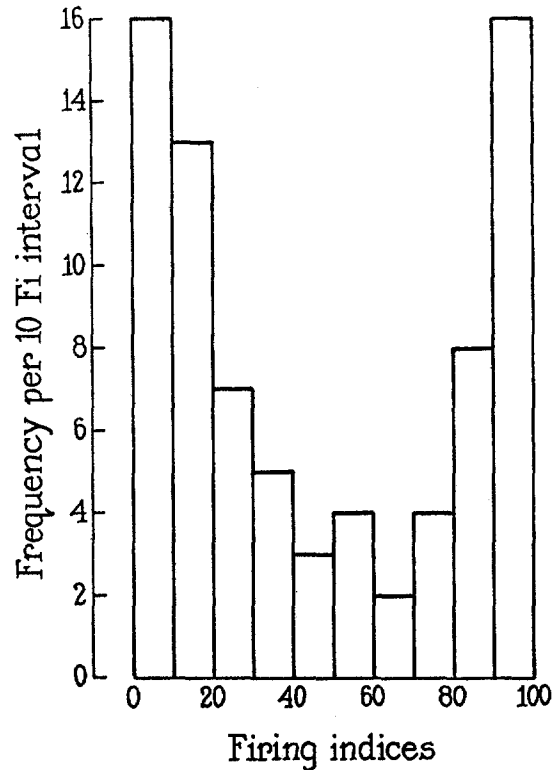


FIG. 3. Frequency distribution of intermediate firing indices of motoneurons.

values obtained at three levels of drive are lumped together. Two frequency maxima are found, these being located at the two ends of the distribution with a minimum, or antimode, toward the center.

The reason for the U-shaped distribution is not difficult to surmise. As earlier stated all  $Fi$  values would be either 0 or 100 if no fluctuation occurred in the system. A corollary is that the manner of fluctuation will determine the distribution of intermediate  $Fi$  values. No practical method exists at present for measuring fluctuation of excitability in individual motoneurons either with respect to range, or frequency distribution of "excitability levels" within the range.

However, for the present purpose the range of "excitability levels" is not important, for this would determine the percentage of intermediate  $F_i$  values in the total synthetic pool rather than the distribution of  $F_i$  values. In this first approximation the distribution of "excitability levels" of a fluctuating motoneuron is assumed to be normal. This will be recognized as nothing more than an extension to the individual motoneuron of the standard assumption underlying the use of mean amplitude of a pool monosynaptic reflex as a measure of pool excitability, a device introduced by Renshaw in 1941 (22). Fluctuation of pool monosynaptic reflex response is measurable and, in order to obtain some working figures, a series of 100 consecutive monosynaptic reflexes was

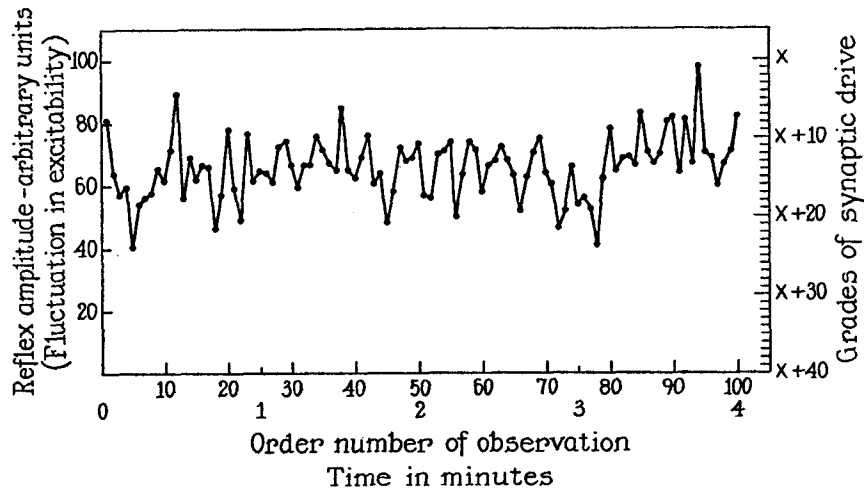


FIG. 4. Amplitude variation of a pool monosynaptic reflex during a 4 minute period encompassing 100 trials. The use to which this sequence is put is described in the text.

recorded at a repetition rate of 25 per minute. Fig. 4 is a plot of reflex amplitudes, in arbitrary units, in the order of observation. According to the extended assumption the plot of Fig. 4 may be considered as representative of excitability fluctuation of an individual motoneuron over a 4 minute interval including 100 trials. To the right of Fig. 4 is a linear scale of synaptic drive extending from some value ( $x$ ) to ( $x + 40$ ). If now 100 trials were made with synaptic drive set at ( $x$ ) by suitable adjustment of the monosynaptic input, the firing index of the motoneuron in question would be zero, for at no time does fluctuation bring the excitability level of the motoneuron above the ( $x$ th) ordinate. Similarly, with synaptic drive set at ( $x + 24$ ), or greater, by adjustment of input, the firing index would be 100, for at no time does fluctuation bring the excitability level below the ( $x + 24$ th) ordinate. In

short, the number of values above each ordinate in 100 trials would yield the firing index at that level of synaptic drive. To the left of Fig. 5 is a plot, con-

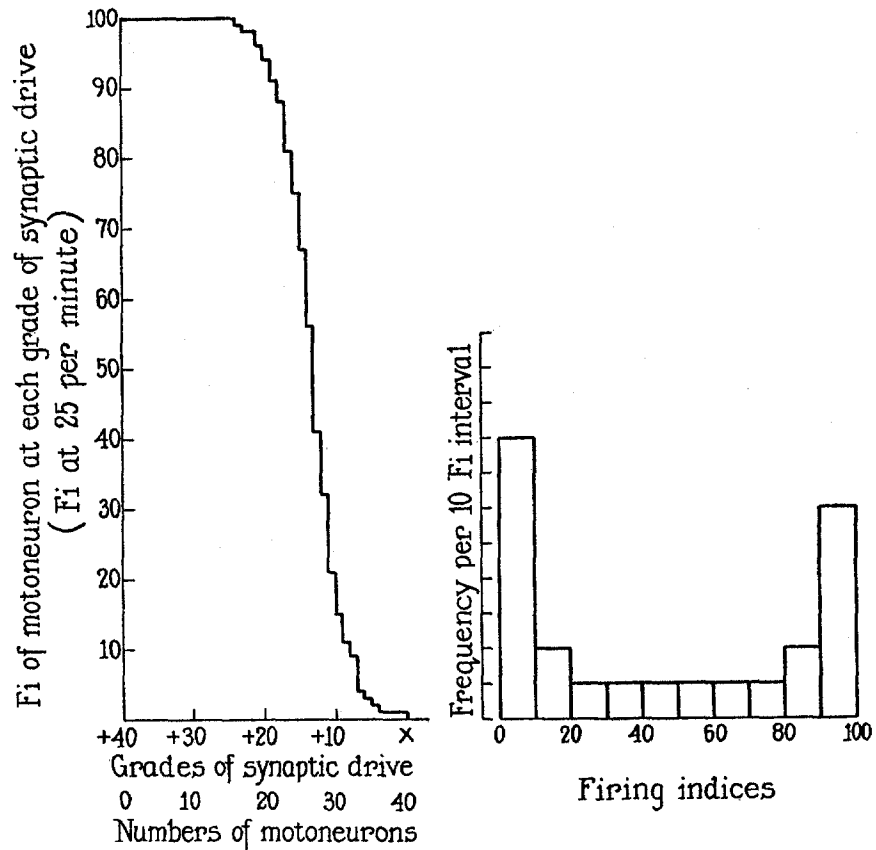


FIG. 5. At left is shown the relation between synaptic drive and firing index of a motoneuron constructed, as described in the text, from the observations in Fig. 4 concerning fluctuation. Assuming motoneurons to be equally frequently distributed with respect to synaptic drive at a fixed input, the relation represents the expected behavior of a normal population with respect to firing indices. Compare with Figs. 1 and 2. At right is a frequency distribution of the intermediate firing indices represented in the construction at left. Compare with Fig. 3.

structed from the data in Fig. 4, that relates firing index of the hypothetical motoneuron to synaptic drive. To the right of Fig. 5 is a frequency distribution of the intermediate  $Fi$  values entered at the left, constructed as in Fig. 3, the class interval being 10  $Fi$  on a "less than" basis.

To this point the constructions in Fig. 5 deal with the hypothetical  $\Delta Fi$  of a

single motoneuron as synaptic drive increases in equal steps from threshold to supramaximal. However, if one makes an assumption to the effect that motoneurons in the intermediate range of a natural pool are evenly distributed with respect to grades of synaptic drive at a fixed input then the constructions of Fig. 5 can be taken as representing the ranking and frequency distribution respectively of a certain number of individual motoneurons with respect to  $F_i$  at a fixed level of monosynaptic afferent input (*viz.* maximal stimulation of the nerve to one head of gastrocnemius). The assumption that has been made will be recognized as that implied in all studies that have utilized monosynaptic reflex testing to determine excitability changes in a spinal motor nucleus.

Correspondence between the constructions of Fig. 5 and the experimental observations in Figs. 1, 2, and 3 suggests that the ordinary assumptions concerning fluctuation and mean amplitudes of monosynaptic reflex responses in a motor nucleus when applied to individuals are adequate to account in the first approximation for the distribution of intermediate firing indices in the synthetic pools.

*Unitary Behavior During Post-tetanic Potentiation.*—It has proved possible to reconstruct from the recorded behavior of individuals a “synthetic” curve of post-tetanic potentiation. To do this each individual motoneuron was subjected to a standard tetanic stimulation (12 seconds at 500 per second) of its homonymous nerve followed by a low frequency (25 per minute) series of test stimuli beginning 2.4 seconds after close of the tetanic conditioning. The pattern of response–no response behavior was recorded for each motoneuron. From this information the cumulative incidence of response for each test stimulation of the standard series was found, the resting values, expressed as number of units discharging, being plotted according to the order number of each test in the series, the final result, however, being expressed as a function of time in minutes. The curve obtained is presented in Fig. 6. For the purpose of the construction it is assumed that the individual motoneurons would contribute equally to spike potential amplitude. In the actual recordings this obviously was not true, for the conditions of recording varied from one to another ventral root filament. However, from the viewpoint of response recorded from a population in an intact ventral root, with which the sum of the responses of individuals is to be compared, the assumption is not unreasonable since the motor axon population (excluding fusimotor fibers) occupies a narrow band at the high velocity end of the diameter-velocity spectrum.

Fig. 6 is based upon the responses of 104 motoneurons, data for the remaining 6 being incomplete, number of post-tetanic responses being known but the pattern of response having been lost by accident. Of the 104 motoneurons 89 responded at the peak of potentiation, the remainder, 15, did not respond at any time. That is, every motoneuron that responded to any post-tetanic trial did so on the seventh.

That the synthetic potentiation curve of Fig. 6 reproduces the course of potentiation in a natural pool in similar circumstances of conditioning and test stimulation (17) is the best available evidence for supposing that the sample is representative, and hence that the method of sequential isolation of motoneurons to the number of about 100 has been adequate for the purpose.

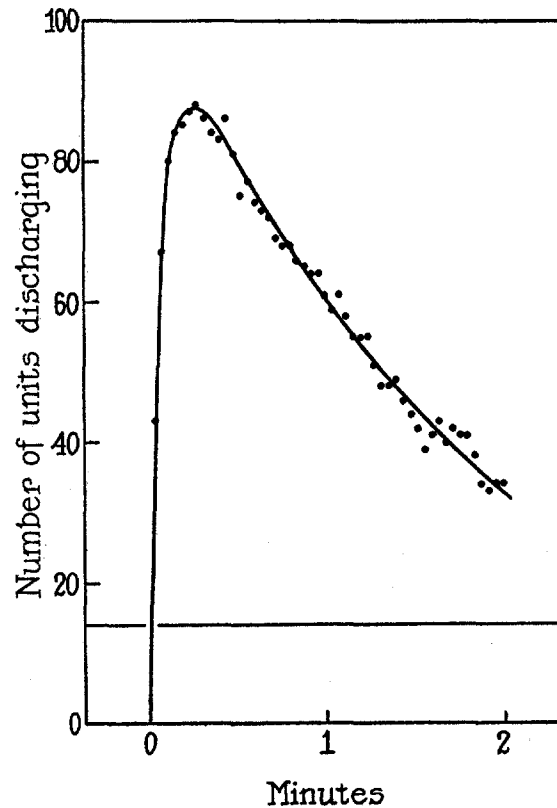


FIG. 6. Synthetic curve of post-tetanic potentiation constructed, as described in text, from observation of behavior of individual motoneurons. Cf. reference 17 for natural curves with which this may be compared.

Obviously most of the post-tetanic responses represent recruitment from the group of  $F_i = 0$  motoneurons in the resting condition. Within this group every degree of intensity of post-tetanic response was encountered, from those that responded to each test during the first post-tetanic minute to those, in number 15, that remained in the  $F_i = 0$  category throughout. When the entire gastrocnemius nerve was tetanized and subsequently utilized for test volleys 14 of that last 15 motoneurons were recruited from the subliminal fringe and again every degree of intensity of response was encountered. In essence post-tetanic

potentiation consists of a temporary increase in the transmitter potentiality of a fixed input at each of its synaptic junctions with motoneurons. By its operation individual motoneurons that otherwise lie in the subliminal zone where they cannot be studied are brought to the discharge zone where they can. The manner in which they then respond implies that the homonymous synaptic connections they receive although all subliminal in the resting state nevertheless are fully and uniformly graded with respect to transmitter potentiality in the range that is represented.

#### REMARKS

*Considerations Relating to the Use of Intracellular Recording.*—While the present study is not concerned with the observation of motoneuron responses recorded by means of intracellular microelectrodes it deals with individuals as must necessarily any study employing the intracellular microelectrode. With the growing popularity of the intracellular technique as well as the isolated axon technique it is important to have some criteria for deciding in a given situation whether a given motoneuron is or is not providing the sought for item of information. Seemingly, the essential criterion must be that the sum of the individual behavior patterns in a given circumstance shall duplicate the behavior of the natural pool in that circumstance. For certain purposes, naturally, one could choose a given segment of the synthetic pool and for some other purposes some other segment. For instance, if one were observing the influence of convergent monosynaptic inhibitory volleys and latency were a matter of concern it would not be necessary to assemble a full range of  $F_i = 0$  neurons in the test series, but if one were to neglect the intermediate zone in the response to test in isolation the information gained would almost certainly be misleading. On the other hand to locate the time of maximum effect would require the inclusion of a representative assemblage of  $F_i = 100$  neurons in the test series, for some of these certainly would drop into the intermediate zone if not into the subliminal fringe at that time.

It might be supposed that the use of intracellular recording would enhance the range of utility of unitary analysis by permitting direct observation of postsynaptic potentials of units throughout the  $F_i = 0$  zone. At the present time, however, there is no assurance that magnitude of an intracellularly recorded postsynaptic potential bears any consistent relation to the transmitter potentiality, or for that matter the facilitator potentiality, of an incident monosynaptic action. Parenthetically, no reason exists for postsynaptic potential to vary with transmitter potentiality for it is now clear that the postsynaptic potential is not an essential step leading to monosynaptic reflex transmission (18). The possibilities for independent variation are many and, unless and until an empirical relation can be established, perhaps by rank correlation between amplitude of postsynaptic potential and post-tetanic  $F_i$  in a number of

resting  $F_i = 0$  motoneurons, the utility of a direct approach into the  $F_i = 0$  range is at best questionable.

*Measurement of Response and of Change in Response in Pools and Individuals.*—It is a commonplace observation that the number of motoneurons engaged in monosynaptic reflex response to a series of identical afferent volleys varies in magnitude from one trial to the next. The basis for variation is fluctuation in responsiveness of the individual motoneurons in the population from which response is obtained. At a given size of afferent impulse input some motoneurons are so strongly excited that they never fail to respond by reason of fluctuation, others are so weakly excited that they never do respond. Between these extremes is a segment of the population, perhaps as much as 30 per cent of the total, excited within a critical range that permits fluctuation to determine whether or not response occurs on any given trial stimulation.

A major distinction exists between studies upon response of populations and of individuals. Population response is measured by extracting the mean in a series of trials and, according to this, dividing the population arbitrarily into responding and non-responding fractions. Change in response is expressed by varying ratio of numbers in the two fractions. In the study of individuals change of status is measurable only as the individual lies in the intermediate zone between the never responding and the always responding condition. This zone that is dispensed with in population studies by statistical apportionment of its members becomes the focus of attention in studies of individuals. As it so happens (*cf.* reference 11) knowledge of the exact manner in which individuals enter into and traverse the intermediate zone before becoming invariable contributors to response amplitude has considerable importance for the interpretation of the relation of mean pool response to input.

*Concerning the Distribution of Motoneurons with Respect to Transmitter Potentiality of Monosynaptic Reflex Connections.*—According to the present evidence it is sufficient accounting in the first approximation for the distribution of intermediate firing indices that "excitability levels" in fluctuation are normally distributed, and that motoneurons within a certain range are equally frequently distributed with respect to degree of transmitter potentiality of their monosynaptic reflex connections. Since the distribution of intermediate  $F_i$  values remains in general the same at several levels of synaptic drive (Figs. 1 and 2), although an almost completely different segment of the population occupies the intermediate zone at each level of drive, it may be supposed that the range of transmitter potentialities throughout which the motoneurons are approximately equally frequently distributed is fairly broad. There is, however, nothing in the available information to preclude irregularity, or a minor trend one way or the other, in the frequency distribution of motoneurons with respect to transmitter potentiality. The experiments here described give no information concerning the upper and lower ends of the scale of transmitter potentiality.

## SUMMARY

Individual motoneuron responses to a variety of afferent inputs have been examined. At a given input some motoneurons respond to every trial, some to no trial, and some respond to a certain percentage of trials that is characteristic for the motoneuron at that input. The performance of a motoneuron is expressed by means of a *firing index* that relates the number of responses to the number of trials.

In a representative assemblage of individual motoneurons some 20 to 30 per cent display intermediate firing indices. This number, comprising an "intermediate zone" remains fairly constant at different levels of input although the individuals within it may be entirely different at two different levels of input.

Frequency distribution of individuals with respect to firing indices is U-shaped.

Intermediacy of firing indices depends upon temporal fluctuation of excitability which, in the first approximation, is normal.

The individual motoneurons are approximately equally frequently distributed with respect to transmitter potentiality of their monosynaptic reflex afferent connections.

The distribution of motoneurons with respect to transmitter potentiality of their monosynaptic reflex connections is considered representative of a natural pool in that the sum of their individual post-tetanic response behaviors accurately reproduces the course of post-tetanic potentiation in a natural pool.

## REFERENCES

1. Adrian, E. D., and Bronk, D. W., The discharge of impulses in motor nerve fibers. Part II. The frequency of discharge in reflex and voluntary contractions, *J. Physiol.*, 1929, **67**, 119.
2. Alvord, E. C., and Fuortes, M. G. F., A comparison of flexor reflexes of cutaneous and muscular origin, *J. Physiol.*, 1954, **123**, 251.
3. Del Castillo, J., and Katz, B., Statistical nature of "facilitation" at a single nerve-muscle junction, *Nature*, 1953, **171**, 1016.
4. Del Castillo, J., and Katz, B., Quantal components of the end-plate potential, *J. Physiol.*, 1954, **124**, 560.
5. Del Castillo, J., and Katz, B., Statistical factors involved in neuromuscular facilitation and depression, *J. Physiol.*, 1954, **124**, 574.
6. Denny-Brown, D. E., On the nature of postural reflexes, *Proc. Roy. Soc., London, Series B*, 1929, **104**, 252.
7. Fatt, P., and Katz, B., Spontaneous subthreshold activity at motor nerve endings, *J. Physiol.*, 1952, **117**, 109.
8. Granit, R., and Ström, G., Autogenetic modulation of excitability of single ventral horn cells, *J. Neurophysiol.*, 1951, **14**, 113.
9. Hunt, C. C., The reflex activity of mammalian small nerve fibers, *J. Physiol.*, 1951, **115**, 456.



10. Hunt, C. C., The effects of stretch receptors from muscle on the discharge of motoneurons, *J. Physiol.*, 1952, **117**, 359.
11. Hunt, C. C., Temporal fluctuation in excitability of spinal motoneurons and its influence on monosynaptic reflex response, *J. Gen. Physiol.*, 1955, **38**, 801.
12. Hunt, C. C., Monosynaptic reflex response of spinal motoneurons to graded afferent stimulation, *J. Gen. Physiol.*, 1955, **38**, 813.
13. Ling, G., and Gerard, R. W., The normal membrane potentials of frog sartorius fibers, *J. Cell. and Comp. Physiol.*, 1949, **34**, 383.
14. Lloyd, D. P. C., Mediation of descending long spinal reflex activity, *J. Neurophysiol.*, 1942, **5**, 435.
15. Lloyd, D. P. C., Neuron patterns controlling transmission of ipsilateral hind limb reflexes in the cat, *J. Neurophysiol.*, 1943, **6**, 293.
16. Lloyd, D. P. C., Integrative pattern of excitation and inhibition in two-neuron reflex arcs, *J. Neurophysiol.*, 1946, **9**, 439.
17. Lloyd, D. P. C., Post-tetanic potentiation of response in monosynaptic reflex pathways of the spinal cord, *J. Gen. Physiol.*, 1949, **33**, 147.
18. Lloyd, D. P. C., On monosynaptic reflex transmission and the postsynaptic potential, data to be published.
19. Lloyd, D. P. C., and McIntyre, A. K., Analysis of forelimb-hindlimb reflex activity in acutely decapitate cats, *J. Neurophysiol.*, 1948, **11**, 455.
20. Lloyd, D. P. C. and McIntyre, A. K., Transmitter potentiality of homonymous and heteronymous monosynaptic reflex connections of individual motoneurons, *J. Gen. Physiol.*, 1955, **38**, 789.
21. Nastuk, W. L., and Hodgkin, A. L., The electrical activity of single muscle fibers, *J. Cell. and Comp. Physiol.*, 1950, **35**, 39.
22. Renshaw, B., Influence of discharge of motoneurons upon excitation of neighboring motoneurons, *J. Neurophysiol.*, 1941, **4**, 167.