A CONTRIBUTION TOWARDS THE DETERMINATION OF THE ENERGY DEVELOPED BY A NERVE CENTRE.¹

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I HAVE first to return my very sincere thanks to the Society for the honour that they have conferred upon the surgical side of Neurology and upon myself in electing me to their presidential chair, and I appreciate the honour the more since it is a position which has been occupied successively by almost all my teachers, prominently among whom is my immediate predecessor, Dr. Savage.

It is the established custom for the person just inducted into the chair to deliver an address, and I am very glad to embrace this opportunity of communicating, if in a somewhat preliminary manner, the results of an investigation which I planned some years ago, and upon which I have also worked from time to time partly in collaboration with Dr. Veraguth and Dr. Christiansen.

The subject matter of this research is an attempt to estimate quantitatively the "work"² done by the central mechanisms of the central nervous system when these discharge their nerve energy; for example, to discover, if possible, the amount of energy developed by the centres in the cortex cerebri and in the spinal cord respectively, the relative volume of the two mechanisms being so very different, see fig. 1. Apart from the general scientific interest of prosecuting this study of nerve energy for its own sake, this subject I venture to think has a considerable

¹ Presidential Address to the Neurological Society.

² Of course the word "work" is not used here in its scientific sense, since we do not know the nature of nerve energy or nerve force. The words "energy" and "force" are also to be accepted in their popular meaning.

importance in relation to the epileptic convulsion, and therefore I bring it forward to-night as a matter of concern to both the physiologist and the clinician.

When we speak of the discharge of nerve energy from a nerve centre it is not a little disturbing to find that we know nothing about nerve energy except the rate of its transmission along the nerve fibres and the circumstances under which it is evolved. It has of course been compared

FIG. 1.

Central Nervous System of the Cat.

to all forms of so-called physical energy, and Newton himself speaks of a nerve impulse as amounting to a vibratory disturbance of the particles of the nervous system.

Nerve energy cannot therefore be measured with any apparatus known to us at present, and therefore if we are to attempt to study its development quantitatively the only

available method of doing this is by indirect means such as quantitative measurement of either some constant correlative phenomenon or of any physical effect directly produced by its activity. I would suggest that there are two possible ways of arriving at some sort of conclusion: these are (1) electrical, (2) mechanical.

(1) *Electrical Method*.—Of these the first is the measurement of the "negative variation" of Du Bois Reymond or "action current" of Hermann, which accompanies, of course, every single so-called nerve discharge or impulse, and which, in a summated form, may be accurately enough estimated by the galvanometer or electrometer.

It will be realised that the electrical method of examining the degree of discharge of a nerve centre is only the quantitative observation of an electrical change in the nerve channels running from the nerve centre which is the seat of stimulation; in other words, the electrical method offers of course nothing absolute but provides the determination of a very important parallel phenomenon, such phenomenon being developed under such circumstances as make it at least likely that a quantitative relationship exists between it and the discharge of nerve energy. So that in a measure the degree of electrical change may be said to be an expression of the degree of development of nerve energy. The proof of this was given by Professor Gotch and myself six years ago when we published in full¹ the results obtained by our method of investigating the functional activity of various parts of the nervous system. Among our facts we included a table giving the readings of the deflections observed when the galvanometer was connected with the spinal cord and the cortex cerebri excited and when, in addition, the general epileptic condition of the upper half of the body was simultaneously noted. I repeat here a table (constructed from experiments on four different animals) which shows clearly that the electrical change or summated action currents in the spinal cord was quite proportional to the degree of discharge from the cortical nerve centres.

¹ *Phil. Transactions*, vol. clxxxii., p. 331, 1891.

GALVANOMETRIC EFFECTS PRODUCED IN SPINAL CORD OF CAT BY CORTICAL EXCITATION. (*Phil. Trans.*, 1891).

	Intensity of Excitation	Duration and Place of Excitation.	Galvanometric Effect	Muscular Move- ment
Cat (31) ..	8,000	5" left cortex	63	Slight fit
	8,000	" right "	115	" "
	9,000	" left "	108	" "
" (317) ..	9,000	" right "	230	Good fit
	8,000	" left "	50	Very slight fit
	10,000	" " "	162	Fair fit
	12,000	" " "	235	Good fit
	8,000	" right "	130	Slight fit
" (319) ..	10,000	" " "	185	Fair fit
	12,000	" " "	230	Good fit
	10,000	" left "	90	Slight fit
	12,000	" " "	170	Fair fit
	10,000	" right "	150	" "
" (324) ..	12,000	" " "	260	Good fit
	6,000	" left "	260	Slight fit
	8,000	" " "	340	Fair fit
	10,000	" " "	510	Powerful fit
Average.. ..			17 = 3288	
			193	

I intend to pursue this branch of the subject with the advantage of the use of the capillary electrometer as recently perfected by Mr. Burch, seeing that with the electrical units now in use the disturbance of energy in the spinal cord channels can be expressed scientifically in terms of work and consequently be directly compared with the records obtained from the muscle by the mechanical method *vide infra*. This has been rendered possible by the recent determination by Gotch and Burch, of the true value of the single "negative variation" or "action current." The unsatisfied condition, however, of course, always still remaining to mar this method, namely, that we cannot know the *precise* scale of parallelism between the amount of nerve energy and the amount of the electrical effect, until some one discovers a means of directly recognising and measuring nerve energy.

(2) *Mechanical Method*.—By this expression I wish to convey the fact that advantage is taken of the connection

of certain muscles with certain nerve centres to accept the work done by the contraction of such muscles as representing the degree of nerve energy evolved from the centre the activity of which produces the contraction. For this purpose we require measurement of the "lift," i.e., height and weight lifted, effected by the discharge of any given centre, as well as the total work done in a given time. I shall on this occasion speak of the "lift" accomplished by the muscle and not the areas of the curves obtained in the experiments which would give the total work done. Provided that the centre examined and motor nerve leading therefrom are subjected to a maximal excitation (maximal because since each of these experiments is a comparison and at the same time involves the excitation of structures very different in nature and excitability as nerve centres and nerve channels respectively are, naturally the stimulus must be maximal) then we know that we have reached the

FIG. 2.

Graphic record of Muscle Contraction resulting from Cortical Excitation.
(*Phil. Trans.*, 1891.)

limit of mechanical effect obtainable from the part excited, and it then becomes possible for us to compare the effect obtainable from the muscle when directly excited from its nerve with that obtained as the effect of the discharge of nerve energy from the centre. From the comparison of these results we gain a relative value. Whereas in the case of the electrical method there is the drawback, as I pointed out, of want of a precise knowledge of parallelism between the correlated phenomena of nerve discharge or electrical "action current"; in this mechanical method we have a larger and more important source of complication and possible error which must now be noted. If we are

applying the method to obtain an estimate of the activity of the centres in the cortex cerebri, it is a fair assumption that the discharge observed arises in the cortex cerebri, but there remains the exceedingly difficult question as to how far the bulbo spinal centres are, or are not, taking part and producing a certain share of the whole effect. To take a concrete example the question is, given excitation of the centres in the cortex we have to enquire whether the total amount of work done by the contracting

FIG. 8.

Schematic representation of electrometric arrangement for estimation of the descending changes in the cord.

muscle is due to the energy of the cortex, or due to the energy of the cortex plus that of the spinal cord; or, to put the matter yet in another way, the question is whether the spinal cord, under these circumstances, is acting as a mere conductor, or whether it is acting as a contributing agent. As regards the *character* of the contractions of the muscle, *i.e.*, tonic and clonic (see fig. 2), this problem was first satisfactorily approached by Franck and Pitres, who, in 1877, found

by the graphic method that excision of the cortex and excitation of the subjacent corona radiata fibres was followed by practical abolition of the clonic element, so characteristic a feature in the effect derived from stimulation of the cortex. This result was confirmed by Bubnoff and Heidenhain (1881), Schafer and myself (1885). From this fact the conclusion was drawn by some observers that the tonic element was due to the lower (bulbo spinal centres). On this point a controversy arose between Ziehen¹ and Unverricht,² which had the effect of emphasising the essentially clonic nature of the discharge of the cortex centres. The

FIG. 4.

Reduced photographic record of the electrometric variations, the cord being connected to the electrometer and the cortex excited.

only proof, however, that could be accepted as really bearing directly on the character of the elements of the cortical discharge was afforded by the electrical method of Gotch and myself,³ where, by interpolation between the cortical and bulbo spinal centres respectively (see fig. 3), the fact that the cortex discharge consists of *both* tonus and clonus elements was finally established. (See fig. 4 and fig. 5, in which latter the action currents of the clonic spasms are

¹ Chief paper "Zur Physiologie der Infra-corticalen Ganglien, &c." *Archiv f. Psychiatrie und Nervenkrankheiten*, B. xxi., p. 863, 1890.

² Chief paper "Ueber Tonische und Clonische Muskelkrämpfe." *Deutsches Archiv für Klinische Medizin.* B. xlv., p. 418, 1890.

³ *Loc. cit. supra.*

more highly magnified.) Still there remains the problem, how far in the intact nervous system does the spinal centre add to the work effected, since it is now clear that the *character* of the whole effect is entirely cortical. At present our data are imperfect and must remain so until by the electrical method the work done in the nerve channel between the cortical and the bulbo spinal system respectively has been measured. Now, as regards the mechanical method, I am going to suggest that for the purposes of the present subject this question of the source of the tonus contraction does not stand in our way of

FIG. 5.

The clonic stage in fig. 4 recorded under higher magnification and more rapid rate.

advancing the subject for the reason that it is possible to first obtain a maximal reflex discharge from the spinal centres, and by that means to discover that the cortex cerebri gives a discharge of more energy than that of the cord, or at any rate, during the first few seconds of the stimulation time. In fact, a relative estimation is easy to make when the effect of a cortical excitation is, as a matter of fact, so much larger than that derived from a direct stimulation of the isolated of the spinal cord. Certain further precautions have to be dwelt upon before we can expect this method, which I only put forward as a means

of indicating the relative powers of the different nerve centres to fulfil all we hope from it.

Description of the Mechanical Method.

The mechanical method I have adopted in these experiments is as follows: All the initial operations were performed under ether narcosis. The cortex cerebri was exposed and kept warm. The muscles chosen have been the biceps brachii or the rectus femoris. The latter appears to be the more suitable muscle, certainly it does not become fatigued so soon, or, rather, the exposure of its nerve is not followed by so much shock as in the case of the biceps. An inextensible thread was carried from the muscle over a small pulley and attached to a small metal bucket running on steel guides and carrying a light aluminium marker. The total weight to be raised by the muscle was made equal to 100 grammes by putting shot in the bucket. This, together with three electrical signals, two for recording the moment of stimulation from the two separate induction coils, and the third, a seconds of time marker, was arranged to write simultaneously either on the paper of a Hürthle Kymographion or on the glass plate of Professor F. J. Smith's chronograph, in which the carrier was drawn forward by slow clockwork. Both sciatic nerves were exposed and ligatures passed beneath them, as also the right anterior crural nerve, where it is buried in the substance of the psoas muscle. A slip of indiarubber sheeting was passed under the latter, and fine platinum electrodes were hooked on the nerve in question lying between the folds of the india-rubber. By use of the second coil it was possible to arrange simultaneous excitation of the different structures. After a tracing had been obtained of the muscular spasm resulting from excitation of the cortex, then where possible a tracing was taken consequent upon excitation of the corona radiata, and when the observations upon the cerebrum had been completed, the spinal cord was divided at about the level of the sixth dorsal vertebra, and everything prepared for

direct observations of the reflex movements. These were investigated in the following way:—both sciatic nerves were firmly tied with ligatures and divided peripherally. At the moment of ligature and of subsequent division a tracing was taken. The reflexes were ascertained by first exciting the central end of the left sciatic nerve, the right rectus femoris being always chosen; and if there was any effect obtainable, the direct reflex was determined by excitation of the right sciatic nerve (central end).

Relationship of the Different Nerve Centres.

I have not in the following research attempted to ascertain any influence of the cerebellum whether exerted upon the cortical or bulbospinal centres respectively. Its supposed function as a controller of the cerebrum, surmised theoretically by Gowers and established experimentally by Risien Russell is paralleled by Löwenthal's discovery¹ of its controlling influence on a certain (extension) share of the reciprocal innervation phenomena of the cervical bulbospinal centres. So, too, I have ignored the influence of the basal ganglia, because we do not know what their function is, and the idea that they participate in so-called purposive acts which we now know to be of cortical origin has, I believe, no real foundation in any scientific fact.² Moreover, it is not easy to see how they could experimentally be excluded by resection because of the close proximity of the fibres of the internal capsule passing from the cortex down to the spinal cord. The connection between the centres in the cortex and the spinal cord is, of course, of importance in the present question. Topographically it has been shown by the simple excitation method originated by Hitzig and Fritsch and so greatly extended by Ferrier, that the frontoparietal region is alone in direct connection with the centres in the spinal cord, whereas the special sense areas, *e.g.*, occipital, temporal, &c., are in undoubted connection with some of the nuclei of the cranial nerves at the base of the

¹ Löwenthal & Horsley, *Proc. Roy. Soc.*, 1897.

² See Beevor & Horsley, *Phil. Trans.*, 1890, p. 49.

brain and bulb. A further proof of this position was also obtained by Gotch and myself¹ by the electrical method, when we found by leading off different parts of the spinal cord to the galvanometer that excitation of other parts of the cortex, *e.g.*, of the occipital lobe, failed to evoke any electrical change in the spinal cord. The nerve centres therefore, which I have chosen for analysis by the mechanical

FIG. 6.

Diagrammatic representation of the reflex arc and connection with the pyramidal fibres (*Phil. Trans.*, 1891.)

method are those only of the limb areas of representation in the parietal cortex and the spinal centres for the limbs in the spinal cord.

Narrowing our considerations then to this degree we enter upon the next preliminary question. What is the nature of the direct connection between the cortical centre and the spinal cord centre looking upon the latter as an

¹ *Loc. cit. supra.*

intermediate stage between the cortical centre and the muscle.

The degeneration method has shown that the fibres of the pyramidal system descend from the cortical centres, pass into the spinal centres for the muscles, and therein come in an unknown way, into relationship with the large ganglion cells of the anterior cornua, from which extend an axis cylinder process down the so-called motor root and mixed nerve to the muscle.

By the electrical method Gotch and myself showed that there is a remarkable diminution in the electrical effect obtained from the spinal centres along the large nerve trunks to the muscles as compared with the effect obtained on the spinal cord by excitation of either the cortex or pyramidal fibres of the corona radiata, suggestive of the view that the spinal centre forms an intermediate station of considerable influence (see fig. 6.)

I have thus far dealt with this matter of the connection of the cortical centres and the spinal centres, because it is one of great importance, and because it enters into some considerations later as well, but it does not have a direct bearing upon the immediate *value* of the mechanical method since we find that just as is shown by the electrical method in the spinal cord, so the contraction of a muscle *i.e.*, work done by the muscle, varies directly with the amount of discharge from the nerve centre. As a matter, therefore, of relative proportion the activity of the muscle is undoubtedly a measure of the activity of the nerve centre. This being so we are then able to use the muscle to measure the relative values of the discharge of the different parts of the system. Before taking up the actual result obtained I would like to point out that by the electrical method Gotch and myself found that excitation of the corona radiata evoked an electrical change in the cord, which was slightly more than half that evolved when the cortex cerebri was excited. In this connection I must repeat that there is properly speaking no second stage or clonic after effect when the corona radiata is excited, and that the galvanometric observations are those of summated discharge effects.

So, too, the electrical effect in the nerve when the spinal centres are caused to discharge by reflex excitation give rather more than one seventh of the deflection observed when the cortex is excited. That the pyramidal system of fibres have practically the same degree of connection with the elements of spinal centres, as the fibres of the other channels is shown by the fact that the amount of the galvanometrical deflection obtained from the nerve when the cortex was excited was equal to that noted in the nerve when the discharge of the reflex spinal centre was passing down it.

FIG. 7.

Arrangement of the Nerve Centres according to the Degree of Work Done.

In employing as the scale of comparison between the respective heights of the contraction of a muscle in raising the weight of 100 grammes I should state at once that I have never seen any discharge from the nerve centre to result in a contraction of the muscle exceed in height that obtained by stimulating the nerve to the muscle, and in fact no nerve centre by any means that I have employed and

described is capable of evoking as much work from the muscle as excitation of the motor nerve to the muscle produces.

FIG. 8.

FIG. 9.

Figs. 7, 8 and 9.—These figures show the varying degrees of "lift" obtained from the cortex cerebri and motor nerve respectively and in association.

Fig. 7.—In this and succeeding photographs of tracings (reduced), the uppermost line marks by an electric signal

the moment and duration of excitation of the sciatic nerve; the second tissue similarly marks the excitation of the cortex cerebri, and later the spinal cord and central end of one sciatic nerve; the third line marks seconds; and the bottom line is the record of the weight attached to the muscle.

In other words, the nerve centres do not cause a complete explosion of the potential contractility of the muscle. Further, the average "lift" derived from the cortex is about three-fifths of that obtained from excitation of the motor nerve.

FIG. 10.

In an experiment conducted for the purposes of comparison such as I have described the cortex cerebri is at an advantage compared to the spinal centres, because clearly the order of events must be that to test the effect of the centres respectively on the same muscle the cortex phenomenon must be observed before the cord is cut for the purposes of obtaining in its pure form the discharge from the spinal centres. Thus the spinal centres in such an experiment are at great disadvantage, inasmuch for a time they are depressed by shock; but in this connection the hyper-excitability which soon supervenes and which was

first minutely described by Franck,¹ counterbalances the error if the excitation results are taken at proper times after the section of the cord. To obviate this I have varied the experiment in different ways.

Allowing for errors in complications just referred to it would appear certain that the discharge from the cortical centre is on the average capable of evoking more work from the contracting muscle than a spinal centre, so that the centres should be arranged in that order cortex first and spinal cord second.

Thus I have performed some experiments in which the spinal cord was divided first, therefore no cortical excitation was undertaken, and only the spinal cord discharges examined with the result that a higher average "lift" was obtained.

Differentiation of the Effects.

(a) *Cortex or Cortical Effect.*—The character of the cortical discharge I have referred to, but I would like to point out that even at the present time the analysis of its components is very incomplete, and now propose to enter at once upon its analysis.

Firstly, the amount of energetic action by the centre, *i.e.*, demonstrated by the degree of the contraction of the muscle, varies inversely as Bubnoff and Heidenhain,² originally showed with the rapidity of the discharge of the centre, or, putting it in other words, with the shortness of the latent period. This fact is the experimental proof of Dr. Jackson's theoretical conclusions³ on this subject.

In taking the whole curve of the muscle contraction from the cortical discharge we see at once that the greatest amount of work is performed as a rule shortly after the commencement of the excitation, that is, at the beginning of the fit; but this varies with the maximal or minimal character of the excitation. A minimal excitation produces a slow discharge of energy from the nerve centre (see fig. 11), and in accordance with the principles just stated resulted in a less

¹ *Loc. cit. supra.*

² *Archiv. f. d. Gesamte Physiologie.* B. xxvi., 1887.

³ "Lumleian Lectures," *Brit. Med. Journal*, vol. i., 1890.

amount of work being executed early by the centre ; whereas the maximal stimulus produces a high tetanic curve from almost the first moment, which is maintained at the same level for a short time, and then in respect of the main-

FIG. 11.

tenance of the application of the stimulus to be discussed presently gradually sinks towards the abscissa line. The moment the stimulus ceases, after a rapid diminution usually to or near the abscissa, there occurs a secondary

FIG. 12.

gradual development of work done, and very rarely this after effect may amount to nearly the height obtained by the primary discharge from the cortex, *i.e.*, of the first stage. (See fig. 12.)

The clonic or secondary stage of the cortical effort usually attains to a certain height practically equal to that of an initial contraction, at least so far as the apices of individual clonic spasms, and this has been looked upon as a direct result of cortical activity. The character of its tetanic average is that of a gradual rise and an equally gradual fall.

The original experiment of Franck and Pitres, showing that when the cortex is cut off and the subjacent fibres of the corona radiata excited there is no clonic or secondary stage, has always been accepted as indicating that the clonic stage is entirely cortical, but actual proof was wanting until as stated above, the electrometer tracing showed that the clonic spasms were innervated by intermittent impulses of a similar rate and degree descending the spinal cord. It is now, therefore, clear that the clonic factor is of cortical origin, but the question remains, What is the source of the work done in the tetanic reinforcing curve of the clonic stage, is this also cortical or of spinal origin?

I have for some time been investigating this in relation to the whole subject of work done by nerve centres, and by varying the experimental procedure hitherto adopted have obtained some additional results.

It seemed to me that if there was this doubt, it could be to a certain degree cleared up if we could exaggerate the phenomenon itself, *e.g.*, by raising the excitability of the whole system, and especially the spinal cord. For this purpose in a certain series of experiments I stimulated, as shown in the tracing, the central end of the sciatic. Bubnoff and Heidenhain found that powerful excitation of the central end of a sensory nerve caused an increase in the amount of "nerve energy" put out by the cortex.

This we shall see is not always correct, and the exception reveals a very important condition of things.

In repeating these experiments in a slightly modified way I found that the tetanus of the *clonic* or secondary stage was increased when the ordinary tracing was taken and at last obtained in one striking instance the accompanying tracing (fig. 13), which shows what I wish to call a

typical spinal cord effect occurring *after* the clonic stage, showing that at any rate in this instance if the spinal cord was in any degree responsible for the tetanus of the clonic stage it must be to a small amount. A similar tracing was obtained and figured by Franck,¹ but is not explained by him.

At this point I think it would be better to take up the question of the discharge from isolated spinal centres.

Discharge from Spinal Centres.—To compare the maximal discharge from the spinal centres with that obtained from

FIG. 13.

The typical "cord" effect is observed in the middle of the three curves as a prolonged tetanus after the clonic stage.

the cortex or corona radiata it is of course necessary to employ an excitation evoking a tetanus; I have done this with the mechanical method, by taking a tracing of a simple reflex action and a crossed reflex.

The simple reflex was obtained from the rectus femoris muscle through the right anterior crural nerve by excitation of the central end of the right sciatic, and the crossed reflex by the excitation of the central end of the left sciatic, the spinal cord being divided just above the middle of the dorsal region. In some cases a preliminary excitation of the cortex

¹ *Iloc. cit.*

was first performed, but in others there was no interference with the parts above the section of the cord. The general results, *i.e.*, the work done by the muscle under these circumstances by simple and cross reflex action are as follows :—

We will first deal with the way in which the spinal cord responds to the simple reflex stimulus in order that we may define what is a characteristic spinal cord effect.

When the cord is excitable there is a very rapid response to the excitation, the weight is raised to the maximal height

FIG. 14.

Simple reflex contractions showing double spike and large terminal spike.

almost at once, and not infrequently there is an initial spike on the curve which may be on the ascending portion of the curve, or even when the curve has reached its maximum. This initial spike I propose to call the "initial effect" to distinguish it from a terminal spike to be described below (see fig. 14).

It is not, however, necessarily of the same nature as the terminal spike, for apart from a genuine rapid contraction an initial spike may be drawn by the momentum of the apparatus. This, however, is easily distinguished from a real contraction rise. The line of the curve then

runs horizontally forwards, more or less, and with indications of a rhythmical or clonic series of spasms (cf. Schafer & Horsley, *loc. cit.*), and with a more or less rapid descent, owing to "fatigue," in accordance with what has to be described directly, until we arrive at the end of the excitation.

In 1884 I had noticed frequently in the case of a spinal cord excitation, the occurrence of a spike at the end of the curve when the excitation was shut off, such spike resembling the large single clonic spasms often observed at the end of a cortical discharge. In 1881 Sanderson and Gotch noticed that when the spinal cord of a skate is caused to discharge the electrical organ of that fish, it does so with an initial spike and a terminal spike. This form of discharge of the spinal centre must be, therefore, something of a very fundamental character if we find it ranging through the animal kingdom at such wide intervals as these; and here, again, it seemed to me that one might be able to bring the phenomenon into prominent relief by exaggerating the excitability of the cord and producing a premature dissolution of the same.

This phenomenon, which we may call the "end effect" of the spinal cord discharge, is closely associated with the question of the existence of a true spinal "after effect," comparable to the clonic stage or after effect derived from the cortex when the stimulus applied to the latter ceases. Without trenching on what has been said, I have now to point out that although in a more normal condition of the spinal cord, that is to say, during the early stages of an experiment, there is often no after effect to be obtained from the spinal cord resembling the clonic stage of the cortical discharge; still, an after effect may be produced at any time.

The after effect of the spinal cord, however, is so entirely different to the clonic stage of the cortical discharge that it is quite unmistakable, and when it is associated with the ordinary tetanic first stage derivable from the spinal cord, it is then so sharply defined as to justify the expression I used above of "typical spinal cord effect."

The form of the after effect varies with the intensity of the stimulus, as shown in the accompanying tracings.

A weak stimulus of 500 from the Kronecker coil gives a spike-formed after effect, which in many cases can be found to be a delayed end effect. I have found every transition stage between these. The usual spiked end effect simply requires to be delayed one or two seconds to be then an after effect. This is the first form of spinal clonic stage or after effect, and may be compared with the end clonic spasm of cortical discharge.

FIG. 15.

Excitation (reflex) of the spinal cord, showing difference of after effect, with (a) weak and (b) strong stimulus.

The second form is seen when a stronger stimulus (4,000 Kronecker coil) is used and when, as also will be seen directly, "fatigue" is showing itself in the nerve centres and assisting in increasing the delay, *i.e.*, intervals from two to six seconds. It, the after effect, begins slowly to reach a very moderate height and dies away slowly, sometimes exhibiting indications of a rhythm. (See fig. 15.) By taking a stimulus intermediate, say 1,000, one can obtain

an after effect, the character of which is intermediate between the two just described. It is interesting to note

FIG. 16.

Cortex excitatory after effects to compare with the foregoing.

FIG. 17.

Cortex excitatory after effect; (a) common form; (b) delayed end effect.

that the difference in character of the after effects is not affected by exaggerating the excitability of the cord.

No doubt with different conditions of dissolution of the cord, varieties more or less clonic in character could be obtained from the spinal cord if the exact moment was fortunately hit upon; a very exceptional case, for instance, was obtained by Schafer and myself in 1884 from the spinal cord of a rabbit. (*Vide Journal of Physiology.*)

We may therefore conclude that *any* nerve centres, whether in the cortex or spinal cord is capable of discharging (as would have been said some time ago "spontaneously") after it has been thrown into excitation by some definite

FIG. 18.

After effects varied by additional excitation of the spinal cord.

stimulus, but that this after effect of the activity of the centre varies both in *character* and *force* according to the nerve centre producing it.

I now wish to show example in fig. 19 that a capacity for producing a second output of work as it were, can be demonstrated to occur during the discharge of the spinal nerve centre itself and is in effect one variety of Franck's *tetanus a renforcement*, as observed by that author to result from excitation of the cortex, this is very well exhibited in

the dissolution of nerve centres by so-called fatigue and other depressing conditions, which subject I will now take up.

Effect of Disease State on the Output of a Nerve Centre.

Gotch and myself found¹ that the electrical effects obtained from nerve centres when the animal was suffering from some general pathological state, *e.g.*, from the severe disease known as distemper, were small. The same thing is true of course as regards the work done by the muscle

FIG. 19.

when the cortex is excited, and the character of the fatigue effect is that in accordance with the facts previously described the tetanus derivable from the cortex is very slowly developed soon fades down again to the abscissa line and that there is no tetanus in the clonic stage, the clonic spasms in fact simply start from the abscissa line and fall back thereto each time.

Another variety of the same thing in degree of discharge of the nerve centre under a hampering condition of this

¹ *Loc. cit. supra.*

kind is that instead of a clonically marked tetanus the cortical discharge consists of a series of closely aggregated clonic spasms.

As regards the spinal nerve centre discharge when affected by general depression effect, *e.g.*, disease, shock, etc., it is characterised by (1) great diminution of the work done; (2) slow development of the same and rapid failure.

Fatigue by Excitation and its Effect on a Nerve Centre.

Concerning the behaviour however of a normal nerve centre the most interesting phenomena are seen when it

FIG. 20.

" Fatigue effects on spinal nerve centres with strong stimuli. Note the spinal after effects.

appears to be exhausted during the continual application of an electrical stimulus. It might be expected perhaps that by Pflüger's laws the increase of the excitatory stimulus would be followed by an increase in the work done by the nerve centre, but this is not the case, and the whole subject it will be found, is a complex and interesting one.

Genuine Fatigue.

The easiest example is to take a reflex action. The following series of tracings show that with a stimulus of only 500 the degree of work done is very great. Prolonged excitation evoked continuous elevation of the weight, which

FIG. 21.

Comparison between fatigue of (a) reflex spinal centre; (b) fatigue of the muscle (on excitation of motor nerve).

FIG. 22.

Fatigue of spinal centre compared with muscle; prolonged excitation.

is only very slowly and gradually lowered, whereas with an excitation of 4,000 the weight is maintained at its maximal height only for a short period and the descent to the abscissa line is very rapid.

I think it is questionable whether this is fatigue at all, or whether it is not rather an interference phenomenon, because if you throw into the cord an excitation of the

afferent end of the opposite sciatic nerve during the fall of the weight towards the abscissa (the original excitation of the same sciatic nerve being continued all the while), it is found that there is a rapid and powerful raising of the weight and also a marked after effect of the kind characteristic of the spinal cord discharge when excited by a strong stimulus.

It cannot be said therefore that the spinal centre is exhausted in the ordinary sense of the word, but that the effect observed is more allied to the process of "inhibition."

FIG. 23.

Effect of weak and strong excitation respectively on reflex centre.

To analyse this correctly, however, involves a review of our present knowledge of the arrangement of the antagonistic muscles in nerve centres. Attention has for some time been drawn by Sherrington, Beever and others to the existence or non-existence of synergic action of antagonistic muscles, and has resulted in showing that when there is an active contraction of a flexor muscle, for example, that there is simultaneously an active relaxation of the extensor muscle.

This was first demonstrated by Sir Charles Bell and has subsequently been the subject of several papers. Several years ago Lowenthal discovered that excitation of the cerebellum evoked the same remarkable phenomenon, and the result of a long series of experiments by him and myself showed that this was due to the action of the cerebellum on the bulbospinal centres. In the same research we showed that the spinal centres themselves are arranged in an alternating fashion and that, for example, excitation

FIG. 24.

Combined excitation. The uppermost line indicates excitation of the central end of the opposite sciatic nerve. Powerful after effect.

of the central ends of similar nerves of the two limbs was followed by opposite motor effects, excitation of the central end of a nerve of the left side evoked a reflex contraction of a flexor, excitation of the same nerve on the opposite side produced a relaxation of that same flexor and contraction of the extensor.

Quite recently these observations have been amplified by Sherrington and Hering, and extended to an analysis of excitation of parts of the cortex cerebri. It is perfectly

clear, therefore, that every kind of nerve centre at present capable of being isolated must be assumed to have the two opposite functions of antagonistic muscles represented in it, the further conclusion from which is that whereas one function may predominate over the other it is possible that an unequal excitation might produce a *confused* result, and might indeed go further, might convert a former contraction of the muscle into an active relaxation of the same. This latter would be called by some inhibition and by others

FIG. 25.

Comparison of after effect following strong excitation with absence of same after weak.

might be translated as being due to exhaustion and premature fatigue of the muscle.

It was for the purpose of distinguishing between these two possible conditions that I have employed the combination of reflex excitation with the primary excitation, the results of which have certainly taken us far beyond what Pflüger's original laws would seem to indicate; and yet at the same time, as the following tracings show, there is, of course, much truth in their general idea that it is

possible to raise the excitability of the spinal cord and get more work out of it. I can now show that the reciprocal innervation may be at the time being adverse, an example of this is shown in the case of a dog, where I found an unusual condition of things existing, namely, that excitation of the central end of the sciatic developed not contraction of the rectus femoris on the same side, but relaxation, just as though the hamstring muscle nerve had alone been stimulated (Sherrington), whereas excitation of the opposite sciatic nerve produced a small but well marked contraction

FIG. 26.

Excitation of motor nerve to muscle to show non-fatigue of muscle in contrast to the fatigue of the nerve centre.

of the muscle. This last effect, the crossed reflex, could be very notably increased by combining excitation of both nerves at once, showing that the general activity of the centre could be raised even under the adverse circumstances before referred to.

Using the same considerations to analyse so-called failure of the cortex on excitation, the following tracings obtained from the cortex of a perfectly normal animal during a series of observations by Dr. Levy on the fatigue

of the cortex cerebri, and for the loan of which I am indebted to him, show, I consider, the same state of affairs to be taking place, for the reason that the after effects are large and followed by the after excitation of the spinal cord to which I have before referred.

Herewith I also wish to record the occurrence of a very interesting delay of the onset of the clonic or after stage following excitation of the cortex cerebri, and which I have noted in cases where the nerve centres have been thrown

FIG. 27.

Excitation of both sciatic nerves (central end).

into an abnormal condition by excitation of the central end of the sciatic nerve. See in fig. 28 the interval especially in the second example between the tonic and clonic stages. Such delay is explicable upon the ground that the opposite reciprocal innervation has been heightened by the abnormal stimulation of the centre.

Correlative Phenomena Observed.

It will be remembered from what has been said above as regards the method of these experiments that the muscle

employed has commonly been the rectus femoris, biceps and supinator longus, but most especially the first of these. During the progress of experiments I noted that the tail muscles exhibited in a very striking way exactly the same degree and kind of contraction as the rectus femoris muscle,

FIG. 28.

but any tonic, *i.e.*, tetanic effect, was more prolonged in the tail muscles than in the rectus. So, too, occasionally, the afferent excitation of the sciatic caused rhythmical contraction of the rectum. Schiff long ago drew attention to the excitability of the centre in the spinal cord for the representation of tail movements.