A MORE ACCURATE CLINICAL METHOD OF DIAGNOSIS OF PERIPHERAL NERVE LESIONS AND OF DETERMINING THE EARLY RECOVERY OF A DEGENERATED NERVE

WITH REPORT OF CASES AND EXPERIMENTAL DATA *

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INTRODUCTION

Since surgeons and neurologists primarily have had to deal with the large number of peripheral nerve injuries resulting from the late war, there has been an unusual number of investigations carried on to determine the underlying principles of nerve regeneration and the best methods of treating them. The physiologic and anatomic features of nerve degeneration, as well as the surgical methods to correct them, have been studied particularly by Howell,[1] Huber,[2]

* This paper was read in abstract before the American Neurological Society, June 14, 1921, Atlantic City.

1. Howell and Huber: A Physiological, Histological and Clinical Study of the Degeneration and Regeneration in Peripheral Nerve Fibers After Severance of Their Connection with the Nerve Centers, J. Physiol. **13**:335, 1892; **14**:1, 1893.

2. Huber, G. C.: A Study of the Operative Treatment for Loss of Nerve Substance in Peripheral Nerves, J. Morphol. **11**:630-733, 1895; Transplantation of Peripheral Nerves, Tr. Chicago Path. Soc. **11** (June 1) 1919; Repair of Peripheral Nerve Injuries, Surg., Gynec., & Obst. **30**:464 (May) 1920.

Ranson,[3] Vanlair,[4] Kilvington,[5] Sherren,[6] Lewis,[7] Langley,[8] Pollock,[9] Tinel,[10] Athanassio Bénisty [11] and others. Few of the researches have combined the physiologic and anatomic methods. The problem, however, on which little advance has been made is the determination of whether a paralyzed peripheral nerve has any regenerative power. To the surgeon this question is of vital importance, for, though we now know that secondary nerve sutures when carried out by the newer methods afford a much better prognosis than was formerly supposed, a nerve suture should be undertaken at the earliest possible moment. Therefore, if it were possible to determine earlier than heretofore that a paralyzed nerve is beginning to regenerate, a great advantage would be gained.

Keith Lucas [12] and Lapicque [13] demonstrated on cold blood animals that there were certain striking differences between muscles with intact

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3. Ranson, S. W.: Degeneration and Regeneration of Nerve Fibers, J. Comp. Neurol. **22**:487, 1912; Non-Medullated Nerve Figers in Spinal Nerves, Am. J. Anat. **12**:67, 1911.

4. Vanlair, C.: De la néurotization du cartilage osseux dans la suture tubulaire des nerfs, Arch. de physiol., norm. et path. **9-10**:595, 1882.

5. Kilvington, B.: An Investigation on the Regeneration of Nerves, Brit. M. J. **1**:935 (April) 1905. Osborne, W. A., and Kilvington, B.: Axon Bifurcation in Regenerated Nerves, J. Physiol. **37**:1, 1908. Kilvington, B.: An Investigation on the Regeneration of Nerves with Regard to Surgical Treatment of Certain Paralyses, Brit. M. J. **1**:1414, 1908.

6. Sherren, J.: Injuries of Nerves and Their Treatment, New York, William Wood & Co., 1908.

7. Kirk, E. G., and Lewis, D. D.: Regeneration in Peripheral Nerves, Bull. J. Hopkins Hosp. **28**:71 (Feb.) 1917; Fascial Tubulization in Repair of Nerve Defects, J. A. M. A. **65**:486-491 (Aug. 7) 1915.

8. Langley, J. N., and Anderson, H. K.: On Autogenetic Regeneration in the Nerves of the Limbs, J. Physiol. **31**:418, 1904. Langley, J. N.: Observations on Denervated Muscle, J. Physiol. **50**:335, 1915-1916; On the Separate Suture of Nerves in Nerve Trunks, Brit. M. J. **1**:45 (Jan.) 1918.

9. Pollock, L. J.: The Clinical Signs of Nerve Injury and Regeneration, Surg., Gynec. & Obst. **30**:472 (May) 1920.

10. Tinel, J.: Nerve Wounds (Monograph), New York, William Wood & Co., 1917.

11. Bénisty, Mme. Athanassio: Formes cliniques des lesions des nerfs, Monograph, Paris.

12. Lucas, K.: On the Optimal Electric Stimuli of Normal and Curarized Muscles, J. Physiol. **34**:372, 1906; On the Optimal Electric Stimuli of Muscle and Nerve, ibid. **35**:103, 1907; The Analysis of Complex Excitable Tissues by Their Response to Electric Currents of Short Duration, ibid. **35**:310, 1907; On the Rate of Development of the Excitatory Process in Muscle and Nerve, ibid. **37**:459, 1908.

13. Lapicque, L.: Sur la theorie de l'excitation electrique, J. de physiol. et de path. gen. **10**:601, 1908; Conditions physiques de l'excitation electrique, J. de physiol. et de path. gen. **11**:1009, 1909; Techniques nouvelles pour l'electrodiagnostic, Compt. rend. Acad. d. sc. **161**:643 (Nov. 22) 1915; Presentation d'un chronaximétre clinique, Compt. rend. Soc. de biol. **78**:695, 1915.

nerve supply and those without any. Adrian[14] confirmed this on human muscles and showed, as we shall see later, that a muscle whose nerve has degenerated requires a current of longer duration to cause a contraction than does a muscle with normal nerve supply, and that all currents are of far shorter duration than can be obtained with ordinary apparatus. To obtain these very short currents Lucas[12] devised his pendulum and Lapicque[13] his "chronaximeter."

For these reasons, therefore, we undertook some experiments on sutured nerves to determine whether by applying the principles laid down by Lucas, Adrian and Lapicque for differentiating normal and degenerated nerves we might throw some light on these questions.

It at once became apparent, however, that there were certain inherent objections to the Lucas pendulum for clinical purposes. It is very heavy and practically nonportable, expensive in construction and difficult to keep in adjustment. Lapicque's clinical chronaximeter uses keys in the circuit, as does Lucas', which are a source of considerable mechanical trouble. For these reasons we have devised, with the assistance of Professor Lindley Pyle, professor of physics at Washington University, an apparatus which we feel does away with these objections.

DESCRIPTION OF INSTRUMENT BY PROFESSOR LINDLEY PYLE

The problem was to incorporate into an electrical circuit an apparatus which could be opened and closed under the control of the operator and permit the flow of a current for a definite and measurable interval of time, approximately only a few ten thousandths of a second. The apparatus was to be so adjustable that the time interval of current flow could be increased by steps up to the order of a hundredth of a second. It was to be so reliable and constant in action that any chosen current pulse could be repeated as to duration of flow at any time the operator required it. Furthermore, the apparatus was to be light and portable yet sufficiently robust to insure permanency in its time constants. For this reason the method of the heavy topped pendulum as used in the Lucas pendulum was discarded and recourse was had to a spring driven device. After several weeks of experimentation the apparatus pictured in Figure 1 was found to fulfil the required conditions.

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14. Adrian, E. D.: The Electrical Reactions of Muscles Before and After Nerve Injury, Brain **39**:1, 1916; The Recovery of Conductivity and of Excitability in Nerve, J. Physiol. **50**:345 (Sept.) 1916; Physiological Basis of Electrical Tests in Peripheral Nerve Injury, Arch. Radiol. & Electroth. **21**:379 (May) 1917; Conduction in Peripheral Nerve and in the Central Nervous System, Brain **41**:23 (June) 1918; Response of Human Sensory Nerves to Currents of Short Duration, J. Physiol. **53**:70 (Sept.) 1919.

A light aluminum wheel approximately 8 inches in diameter is mounted on a ball-bearing shaft fastened to a bed-plate of brass $\frac{3}{16}$ inch in thickness. One end of a helical coil of steel wire is secured to the bed-plate, the other end being fastened to the wheel. The fundamental idea is to wind up the spring by a rotation of the wheel to a definite position. The wheel, on being released, acquires a high peripheral speed and then automatically brings into action a sliding contact of an attached metal brush across a stationary copper plate of variable width mounted close to the wheel rim. A current flows during the time of contact.

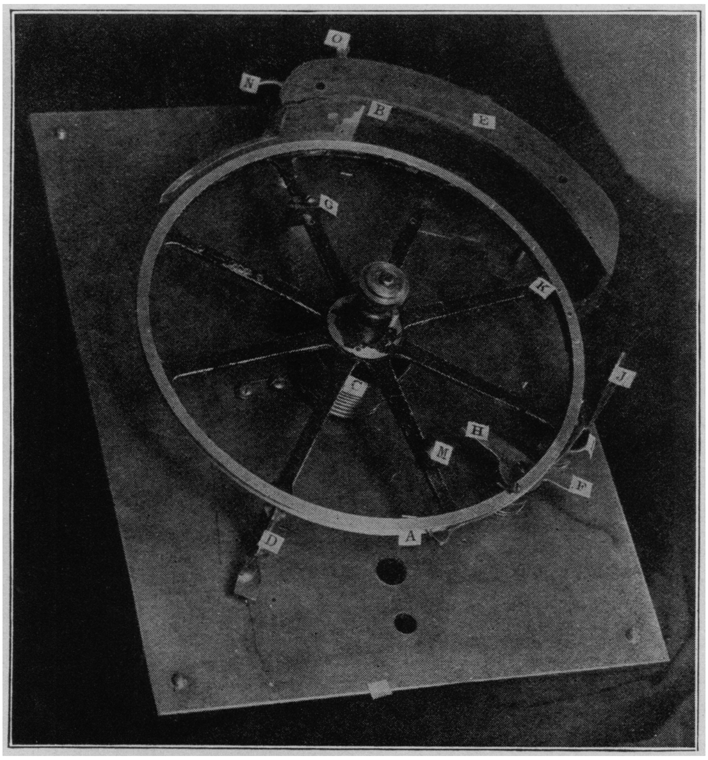

Fig. 1.—Chronomyometer.

Referring to Figure 1, the knob *M* is grasped by the hand and the wheel is rotated right-handedly through about one and a half revolutions. A trigger *D* is then raised to engage with a pin *K* mounted on the lower side of the wheel rim. The mechanism is now "set," ready for operation, and awaits only the depression of the trigger, *D*. A piece of spring-brass wire is mounted on the periphery of the wheel as shown at *A* and constitutes the brush referred to. The outer angle of the wire brush is faced with a strip of platinum soldered to the wire. The block *E* is made of nonconducting red fiber composition so shaped as to have a curved surface concentric with the axis of the wheel. Embedded in this fiber and inlaid so as to be flush with its surface is a piece of heavy-gage copper, *B*, cut into five "steps," or widths, as indicated. A binding post, *O*, is in metallic connection with the copper plate, *B*, by means of a screw penetrating the fiber block. A second binding screw (not shown) is soldered to the brass bed-plate. The fiber block is supported on two brass rods that run through two holes in the bed-plate. A set-screw at *N* may be clamped against one of the support rods so that the fiber block may be set at any desired position. A leather-faced brake-shoe is held away from the outer face of the wheel by a trigger *F*.

The mechanism being set for action and included in the desired electrical circuit by connections to its binding posts, the trigger *D* is pressed and the wheel gathers speed under the action of the stressed spring *C*. The spring-wire brush, *A*, ultimately rides up upon the fiber block, *E*, and, dragging along its smooth surface under a firm pressure, it crosses the copper plate, *B*, at high speed closing the electrical circuit for a definite interval of time. Just after *A* has broken contact with *B* a strip of brass swinging from a pivot mounted on a wheel-spoke at *G* strikes *H* and disengages the trigger *F*. A powerful spring attached to *J* throws the brake-shoe into contact with the periphery of the wheel and brings it to rest before the inertia of the wheel puts a backward twist into the spring, *C*, and before the brush, *A*, passes *B* the second time.

It was found necessary to give the brush at least a 4-inch travel along the fiber block before it crossed the plate *B* in order that any vibration and chattering of the brush due to the initial impact of the brush with *E* might be damped out before the closing of the circuit occurred—otherwise the contact was uncertain. It is desirable to wipe the rubbing surfaces of *B* and *A* and *E* with a piece of chamois to remove dust before each trial. At frequent intervals the faces of *A* and *B* should be wiped with a piece of chamois impregnated with the finest emery dust. With these precautions one may feel assured that at any time a current pulse may be reproduced of unvarying time lapse for any chosen position of the contact plate, *B*.

The duration of contact for each of the five widths of *B* were obtained by an electrical method. A nonabsorbing mica condenser of known capacity was charged through a known resistance by a long-time contact with a battery. The accumulated charge was discharged through a ballistic galvanometer, and the throw noted. With the same circuit constants the condenser was given a short-time charge through the contact-maker under discussion and the ballistic throw corresponding to the short-time charge noted. By a formula known to physicists the duration of the short-time contact was calculated.

The duration of contact for each of the widths of plate were found to be 0.00015 second, 0.00033 second, 0.00065 second, 0.0008 second and 0.009 second. From these figures it is readily determined that each 1 mm. width of copper plate produces a contact approximately 0.000082 second in length. It is possible to secure any value of current duration desired by having a series of copper plates, *B*, of varying widths.

The instrument described we have called a "chronomyometer" because it enables one to measure the time of flow of a current necessary to cause a muscle to contract whether the nerve supply is intact or degenerated.

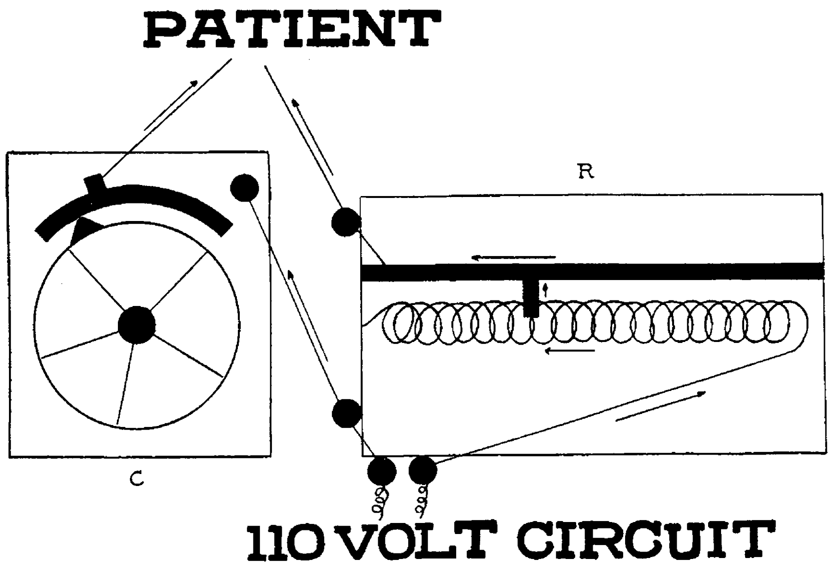

Fig. 2.—Diagram of apparatus.

Prolonged use seems to show that the device is consistent in its action and that any possible variations in the elastic properties of the driving spring are inappreciable.

Figure 2 is a diagram of the electrical apparatus and connections when in use. The chronomyometer, *C*, is in series in the circuit so that the current is flowing only when the brush, *A*, of Figure 1 is in contact with the plate *B* of Figure 1. A resistance coil, *R*, is also placed in the circuit in series so that the voltage of the current used could be varied from 0 to 110 volts. The amperage varies between 6 and 8 milliamperes. A direct current must always be used, and if only an alternating current is available, the direct current may be generated by a small direct current dynamo which is driven by an alternating current motor.

In testing a patient a large indifferent electrode is connected to the positive pole (anode) and an ordinary 1 cm. diameter stimulating electrode to the negative pole (cathode).

The arbitrary values of the duration of the current which the chronomyometer delivers were selected because we felt that any shorter steps would be of no clinical value and would make the procedure too complicated. A nerve-muscle-complex of 0.0008 second was selected as the longest for it was felt that in exceptional cases, at least, a current of longer duration might fall within the limits of a rapid muscle complex and thus lead to false conclusions.

The method of testing is briefly illustrated by the following example: Suppose we want to test a gastrocnemius that has no voluntary movement. The indifferent electrode is placed on the thigh on the same side, the stimulating electrode on the gastrocnemius motor point, the apparatus is set so that the duration of the current corresponds to the longest nerve-muscle complex, 0.0008 second; start with a voltage of about 30. If no contraction follows, gradually increase the current strength until a contraction is obtained. If we obtain none with 110 volts we consider no nervous tissue is present, and the procedure is repeated using the muscle complex 0.009 second and starting with 10 volts; if this fails to cause a contraction a longer duration of current may be obtained by making the contact by hand. On the other hand, if a contraction follows stimulation with the current that gives the longest nerve-muscle complex, the duration is shortened until the minimum duration, no matter how strong the current, which will cause a contraction is obtained. We also determine the least voltage that is necessary to get a contraction at this minimum duration.

PHYSIOLOGIC PRINCIPLES OF MUSCLE AND NERVE-MUSCLE RELATIONS BASED ON A CONSIDERATION OF THE LITERATURE

The more recent investigations on the properties and electrical phenomena exhibited by muscles and nerves have been carried on primarily by Keith Lucas,[12] Lapicque,[13] Sanderson,[15] Adrian,[14] Gotch,[16] and A. V. Hill.[17] To understand this work properly a clear conception

15. Sanderson, J. Burdon: The Electrical Response to Stimulation of Muscle, and Its Relation to Mechanical Response, J. Physiol. **18**:117, 1895.

16. Gotch, F., and Burch, G. J.: The Electrical Response of Nerve to Two Stimuli, J. Physiol. **24**:410, 1899; The Effect of Local Injury Upon the Excitatory Electrical Response of Nerve, ibid. **28**:32; The Submaximal Electrical Response of Nerve to a Single Stmulus, ibid. p. 395; Gotch, F.: The Delay of the Electric Response of Nerve to a Second Stimulus, ibid. **40**:250, 1910.

17. Hill, A. V.: A New Mathematical Treatment of Changes of Ionic Concentration in Muscle and Nerve Under the Action of Electric Currents, with a Theory as to Their Mode of Excitation, J. Physiol. **40**:190, 1910.

is necessary of the excitation time of nerves and muscles, the term applied to it by Lucas.[12]

The excitation time is based on two factors: (1) the minimal strength, and (2) the minimal duration of a constant current, that is, a current which reaches a certain voltage immediately and maintains this voltage as long as it is flowing, in contradistinction to a condenser discharge whose current gradually decreases in intensity. It is also important to realize that constant or galvanic currents and faradic currents are the same kind of electricity, faradic differing from galvanic only in that it flows intermittently for short periods of time.

If one stimulates a nerve muscle preparation with a constant current it is found that the contraction of the muscle is dependent not only on

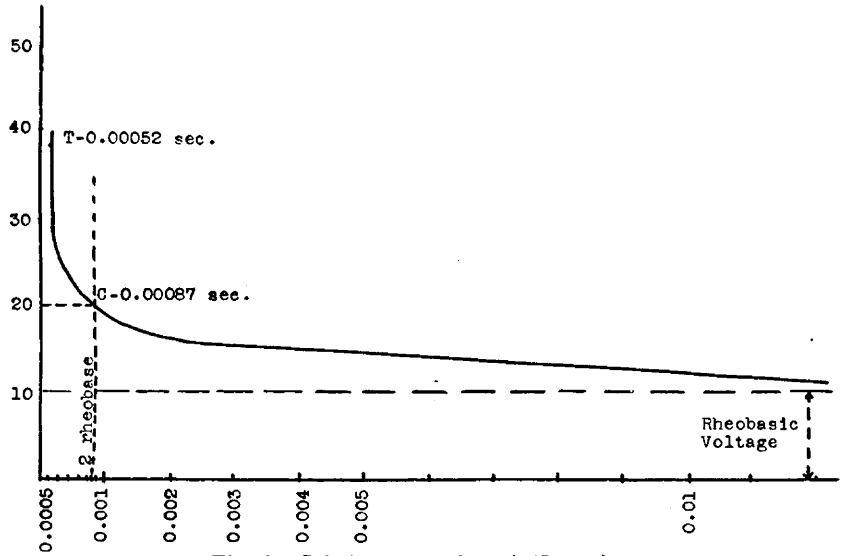

Fig. 3.—Sciatic nerve of toad (Lucas).

the strength of the current, but also on its duration. No matter how strong the current is, that is the voltage, the current must flow a certain length of time in order to get a contraction, and if this is shortened no reaction follows. Conversely, no matter how long the current flows, if the current is not more than a certain strength, no contraction of the muscle will be obtained. Between these extremes as the duration of the current is decreased the strength of the current must be increased to produce a contraction, and vice versa, the duration has to be increased as the strength is decreased. In order to understand the relationship between these two factors, the minimum strength and the minimum duration must be determined in each case. Lucas and Adrian have shown this graphically both in a toad's muscle (Fig. 3) and in a human tibialis anticus with intact nerve supply (Fig. 4). The ordinates show the strength of current, the abscissae the duration of the current. The minimum duration of a current necessary to stimulate a muscle without nerve supply is much longer than that necessary to stimulate a muscle with an intact nerve (Fig. 5).

An analysis of these curves shows that at long, or, as they called it, "infinite" duration there is a minimum strength below which no contractions occur, and as the duration is decreased the strength must be increased until a point is reached where, no matter how strong the current, no contractions follow. This minimum of duration is the measure of the excitation time. The minimal strength current of infinite duration necessary to get a contraction, Lapicque [13] called rheobasic voltage. He noted that a sudden change in the curve occurred approximately at a point at which twice the rheobasic voltage was used and the length of time the current flowed with this strength he called chronaxie. Adrian [14] has found that the chronaxie of a human muscle with intact nerve supply was about 0.00016 second while the chronaxie of a muscle whose nerve had degenerated was about 0.01 second.[18]

We want to emphasize that the chronaxie is not the same as the absolute minimum duration of current required to produce a contraction. In a muscle with intact nerve these two points differ slightly, as shown in Figure 4, the difference being 0.00010 and 0.00016 of a second, while when the nerve is degenerated the difference in these points is very great (Fig. 5), 0.003 and 0.01 of a second.

The difference between the chronaxie of nerves and muscles explains why a muscle whose nerve is degenerated does not respond to the ordinary faradic current but only to the galvanic, for the duration of each faradic shock is shorter than the chronaxie of muscle while the galvanic current is always much longer in duration than muscle chronaxie. The repeated shocks of a faradic current make it impossible for the patient to endure a strong enough current to stimulate the muscle when its nerve supply is impaired, and thus it is of limited clinical value.

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18. The length of the chronaxie of normal muscles and muscles without nerve supply recorded by Lapicque in his first report (Techniques nouvelles pour l'electro-diagnostic, Compt. rend. Acad. d. Sc. **161**:643 [Nov. 22] 1915) agrees very well with Adrian's (The Electrical Reactions of Muscles Before and After Nerve Injury, Brain **39**:1, 1916. Physiological Basis of Electrical Tests in Peripheral Nerve Injury, Arch. Radiol. & Electroth. **21**:379 [May] 1917), but in his second report (Presentation d'un chronaximétre clinique, Compt. rend. Soc. de biol. **78**:695, 1915) it is about ten times as long. As our results correspond to those of Adrian's we feel that his figures are more nearly correct. The difference in Lapicque's figures may be due to the calibration of his chronaximeter.

CLINICAL APPLICATION OF CHRONAXIE

Adrian[14] has used the Lucas pendulum with interrupting keys to vary the duration of the current and a potentiometer to vary the strength of the current. With this apparatus he has determined the curve for a muscle with intact nerve supply (Fig. 4), a muscle without nerve supply (Fig. 5), and a muscle with incomplete division of its nerve (Fig. 6). It will be noted that in Figure 6 the curve has two phases; in reality, therefore, it is fair to assume that there are two separate curves as indicated by the dotted lines; one of these represents the strength-duration curve of a muscle without nerve supply with a chronaxie of 0.004 second (curve A) while the other represents the strength-duration curve of a muscle with intact nerve supply with a

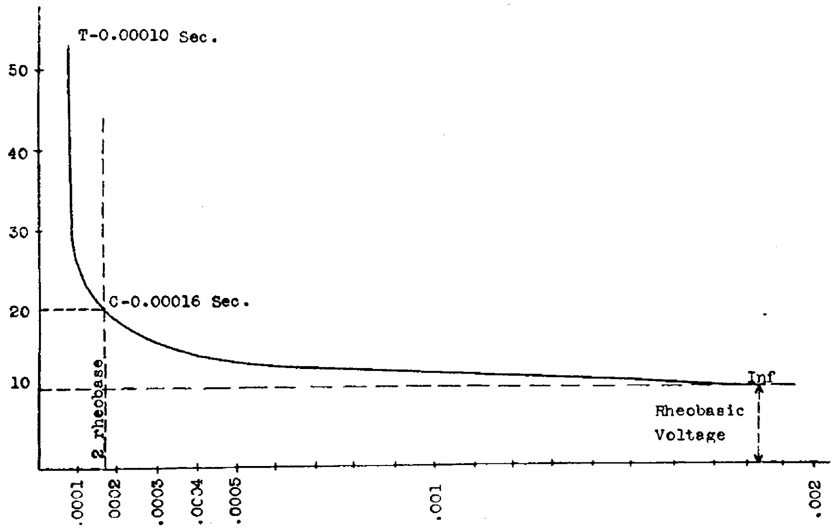

Fig. 4.—Human tibialis anticus, intact nerve supply (Adrian).

chronaxie of 0.0005 second (curve B). This means that if we consider chronaxie as the measure of the excitation time of the tissue we would conclude that 0.004 second meant that only muscle fibers were present. If, however, the true minimum duration of the current is used as the measure of the excitation time of the tissue, it will be seen to be less than 0.0005 second and this would mean that some nerve tissue is present. *We feel that the true minimum duration of the current, no matter how strong the current, is the real measure of the excitation time of the tissues in question and we therefore have disregarded arbitrary chronaxie in our tests.* Cases 4 and 10 illustrate this very well.

Case 4.—On September 18 the rheobasic voltage was 20 V, the chronaxie at 40 V, twice rheobase, was 0.009 second, and thus one would conclude that there was no nerve tissue present. The minimum duration, however, was 0.00033 second with 100 V, and thus we concluded that some nerve fibers were present in the muscles tested and gave the patient a favorable prognosis. The ultimate recovery of voluntary power in these muscles bears out our opinion.

In order to avoid confusion we prefer to use the terms "muscle complex" and "nerve-muscle complex." By muscle complex we mean that the minimum duration of the current necessary to stimulate a muscle falls within the range of time determined clinically and experimentally for muscles without their nerve supply, 0.02-0.004 second; by the term "nerve-muscle complex" we mean that the minimum duration of the current necessary to stimulate a muscle falls within

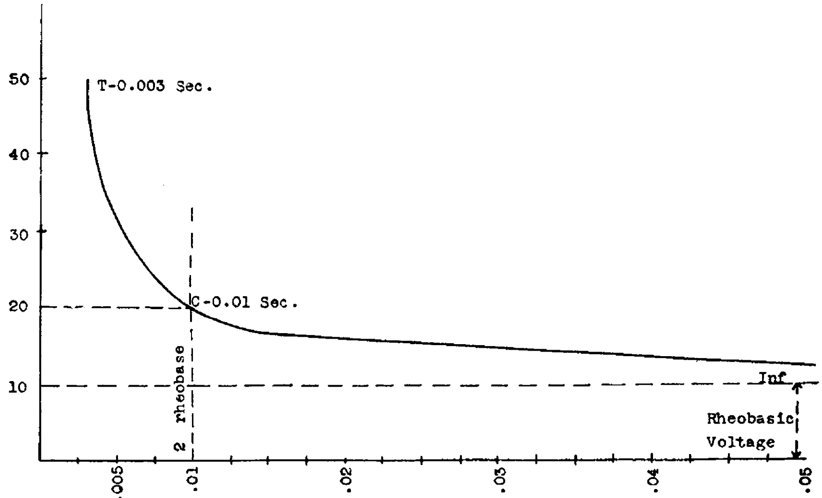

Fig. 5.—Human tibialis anticus, six months after division of sciatic (Adrian).

the range of time determined clinically and experimentally for muscles with intact nerve supply, 0.0009-0.00008 second. The terms long, medium and short are added to indicate whether the nerve-muscle complex is normal or approaching normal, the short response being the normal.

From the three factors, the type of contraction, the minimum strength of current and the minimum duration of the current, the degree of impairment of the nerve supply and the condition of the muscles are determined, and by repeating these tests at varying intervals the progress of the case may be followed accurately. The changes that occur in these cases may be observed by a study of our protocols.

Before considering our own results it will be necessary to point out what we believe to be the objections to previous methods that have been used for testing nerves and muscles.

DISCUSSION OF OTHER METHODS

Chronaxie.—Adrian [14] considers chronaxie the important criterion of the condition of the tissues but also insists that the full curve should be determined in each instance so that a two phase curve, as shown in Fig. 6, will not be overlooked.

This method has the practical disadvantage, however, of taking hours to make these determinations in cases in which a number of muscles are involved and besides, we believe, the determination of the complete strength duration curve is unnecessary.

He, however, also makes this statement: [14] "A current of 0.004 second will excite nerve fibers if it is strong enough, but it will not

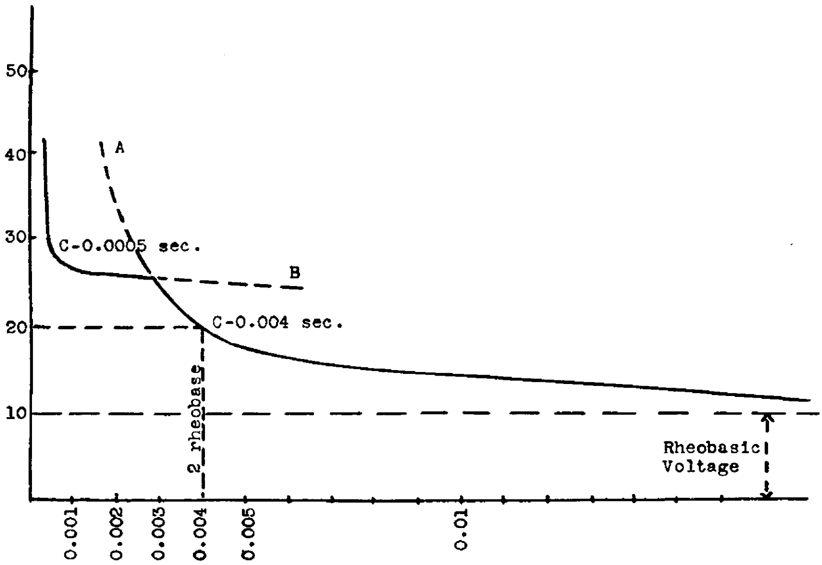

Fig. 6.—Incomplete sciatic injury, human (Adrian).

stimulate muscle fibers, however strong it may be. So if we could always use a current of this duration and of variable strength there would be no need to determine the full curve." Such a method would be essentially what is done with a faradic current unless Adrian means to use only a single shock instead of the repeated shocks of a faradic current but even then a change in the nerve muscle complex could only be detected by the variation in the minimum strength of current used.

According to Adrian the important criterion of regeneration is the decreasing strength of current necessary to bring out nerve muscle chronaxie after it has once begun to appear. As will be seen later, we have found that the change in the minimum duration of the current is the most important criterion.

The minimal strength of current will vary with the tissue resistance, temperature of the muscle, etc., even if there were no change in the innervation of the muscle tested. On account of this great variation in tissue resistance the minimum duration of the current and not the minimum strength of the current must be used as the measure of the excitation time, and consequently the determination of the full strength-duration curve is unnecessary.

The objections to chronaxie determinations are that they do not give the true minimum duration and thus facts are disregarded that we believe are of vital importance in determining the regeneration of a nerve. Also true nerve-muscle chronaxie has seldom been observed in injured nerves until regeneration is nearly complete and at that time voluntary movement has begun to appear.

Condensers.—Condenser systems of the Lewis Jones [19] type enable one to test a muscle with currents of different duration, but Jones [19] himself points out that if the current strength is altered the time of discharge of a given condenser is also altered. Hernaman-Johnson [20] has devised an apparatus to change the voltage of Jones condensers, but this does not regulate the time of discharge which is affected by the voltage. The time of discharge for different voltages could be calculated, but for clinical purposes this is impracticable. Furthermore, a condenser of known capacity charged with a constant voltage discharges in a definite time, but as it discharges the intensity of its current decreases gradually to zero. Roberts [21] has pointed out that a portion of such a discharge is below the minimum strength of a current, at infinite duration, necessary for stimulation, and this portion is ineffective. Since the resistance of tissues varies greatly at all times, the size of the minimum strength current necessary to stimulate a muscle will vary. It follows, therefore, that the amount of current which is below the minimum strength will vary with this resistance, and the duration of the effective part of a condenser discharge varies greatly even though a given condenser is charged with the same voltage. For this reason the value of the constant current becomes apparent for it attains its maximum voltage at once, and this is maintained throughout the period of flow.

For these reasons it is obvious that the results obtained with condenser discharges when compared to tests on normal muscles or previous tests on any muscle are unreliable.

19. Jones, H. L.: The Use of Condenser Discharges in Electrical Testing, Proc. Roy. Soc. of Med. **6**:49 (Jan.) 1913; Medical Electricity, Ed. 6, London, 1913.

20. Hernaman-Johnson: Use of Condensers in Diagnosis, Prognosis and Treatment of Muscles Following Nerve Injuries, Lancet **1**:396, 1916.

21. Roberts, F.: Degeneration of Muscle Following Nerve Injury, Brain **39**: 297, 1916.

Galvanism and Faradism.—The objections to this method of testing muscles electrically have been pointed out by many observers and may be summarized as follows: First, faradism usually returns at about the same time that voluntary movements return, and therefore is of little clinical value. This fact does not appear to be in harmony with the previously stated physiologic facts, but this discrepancy is explained by the fact that the faradic current is a repeated series of shocks, each one having the duration of a long nerve-muscle complex. In cases of regenerating nerves before voluntary movement has returned we shall see that it is necessary to use currents of relatively strong voltage to produce contractions. When this voltage is used with an induction coil, the pain is so great that it is unbearable and in addition the current spreads to surrounding healthy muscles rendering conclusions difficult or impossible. Second, the duration of the faradic shock cannot be varied and would be of no value in showing the progress of a case even if a response could be elicited before voluntary contractions returned. Third, the comparison of the response to negative and positive threshold galvanic currents varies in normal muscles, and when strong currents are used it is difficult to distinguish between the return to normal of stimulated antagonist or neighboring muscles, and the slow contraction of the muscles being tested. The threshold strength varies several milliamperes if exactly the same motor point is not stimulated each time. This renders tests from month to month of little value. Fourth, the entire procedure is time consuming, requires considerable experience and is difficult to interpret.

RELATION OF INDUCED WAVES OF OPENING AND CLOSING (LAUGIER [22])

This method supplies a means of testing a muscle with varying strength of current but only the duration of one muscle complex and one nerve-muscle complex. These values are dependent on the individual coil employed, and a ballistic galvanometer is necessary to determine the strength of current used. The results must be expressed in relative figures derived by dividing the current used in the closing wave by the current used in the opening wave. Objections to this method are: First, the variable is the strength of current which is dependent on many other factors than the condition of the muscle in question; second, the duration of the current cannot be varied; third, the method is technically difficult to carry out; and fourth, the apparatus is not readily transported.

EXPERIMENTAL DATA

In the course of some experiments on methods of repair of peripheral nerves in dogs, the muscles innervated by these repaired nerves were

22. Laugier: Biol. méd. 1914, p. 89.

tested electrically with our chronomyometer. Other experiments were carried out in order to test the changes in the nerve muscle complex during degeneration and regeneration of an injured nerve. The nerves were exposed under ether anesthesia from time to time under strictest aseptic precautions, and thus by direct stimulation of the nerve trunks with the faradic current we determined when regeneration had occurred and the results compared with the chronomyometer findings. Nerves were excised from time to time in order to check up by histologic studies the stage of regeneration of the nerves. All specimens were stained by the Silver-Pyridin method described by Ranson.[3] In all we have done eight nerve sutures, and fifty observations were made on them. (The factor of pain was entirely eliminated by the use of ether anesthesia.)

A study of the tables and protocols of our experiments reveals the following facts:

The nerve muscle complex remains normal for a period varying from forty-six to seventy hours after cutting the nerve trunk (Exper. 89, 91, 93, 113 and 121). In no case was a nerve-muscle complex found on a dog after seventy-five hours.

When the irritability of the nerve begins to diminish it changes rapidly and within from two to five hours only the muscle complex is present. In Exper. 93 the nerve-muscle complex did not begin to disappear until some time between the fiftieth and sixty-eighth hour, but then in one hour and forty minutes it changed from 0.00033 second to 0.00065 second, to 0.0008 second, and then to 0.009 second, the muscle complex. Throughout these tests the same voltage was always used.

As regeneration occurs the slow nerve muscle complex appears first, and then gradually the nerve-muscle complex shortens until it finally becomes normal, 0.00015 second. In these experiments the animals were anesthetized so that the factor of pain could be eliminated and the strength of the current could be increased to the point at which the current was seen to spread to normal muscles.

Faradic response was only elicited when the nerve muscle complex was normal. It could not be elicited earlier even under anesthesia, for when currents as strong as those used with the chronomyometer were used with faradic stimulation, the current spread to normal muscles so that accurate observations were impossible. Whenever the nerve-muscle complex begins to appear it is an evidence of return of regeneration. This we have checked up by histologic examination and by direct stimulation of the nerve trunk (Exper. 51, 81, 91, 99, 113 and 121).

EXPER. 51.—Double lateral anastomosis of peroneal nerve to tibial nerve, tested 221 days after operation and nerve-muscle response 0.00015 second in muscles of peroneal and tibial distribution. Central tibial nerve cut and tested eighteen days later, showed 0.00015 second over peroneal nerve distribution and 0.009 over tibial nerve (with and without anesthesia). Direct stimulation of nerve trunks gave no tibial nerve response but normal peroneal response. Microscopic sections of tibial nerve showed no axis cylinders.

Summary: Nerve-muscle complex before cutting, muscle complex eighteen days after, confirmed by direct stimulation of nerve trunk and histologic examination.

EXPER. 81.—Double lateral anastomosis of peroneal nerve to tibial nerve, tested 106 days later. Reaction: 0.00015 second in anterior and posterior muscles of leg though those innervated by peroneal nerve very weak. Direct stimulation of nerve trunks gave active response of those innervated by tibial nerve but very weak over peroneal nerve distribution. Microscopically there were fewer axis cylinders in the peroneal nerve than in the tibial nerve.

Summary: Weak muscular response to 0.00015 second checked by direct stimulation of nerve trunk and microscopically.

EXPER. 93.—Left sciatic cut and resutured. Nerve-muscle complex 0.00015 second before cutting and for 50 hours after, 0.00033 second 68 hours after operation, 0.00065 second 50 minutes later, 0.0008 second 20 minutes later, 0.009 second 30 minutes later. The voltage was the same in all tests.

Summary: Nerve-muscle complex normal 50 hours after cutting, almost normal 68 hours after cutting but 1 hour 40 minutes later only muscle complex present, that is, irritability of nerve normal for 68 hours after cutting but irritability lost rapidly when it started to decrease.

EXPER. 99.—Nerve tested three months after regeneration and 0.00015 second response found, confirmed by direct stimulation of nerve trunk.

EXPER. 113 and 121.—Opened three days after cutting the nerve, and direct stimulation of its trunk failed to cause muscular contractions. Only muscle complex present. Histologically beginning degeneration.

Summary: Muscle complex after three days; no response to stimulation of nerve trunk and beginning degeneration histologically.

EXPER. 89.—Left sciatic cut and resutured—motor points of left leg tested in each case. Details of this experiment are given in Table 1.

EXPER. 91.—Left sciatic cut and resutured—motor points of left leg tested each time. The details are given in Table 2.

CLINICAL CASES

In the past year about thirty-five cases of peripheral nerve lesions have been tested with the chronomyometer. Many of these patients have been followed with frequent examinations until recovery was complete. Others have not completely recovered as yet, while some have either not returned for examination or the examination was not considered of value, as in cases in which the lesion involved the central neuron.

In each case the following points were studied: sensory changes, trophic disturbances, voluntary control of muscles, functional disability and electrical tests (the chronomyometer was used in all cases and faradism in many). We also looked for Tinel's sign and the pinching test of Athanassio Bénisty. Of the thirty-five cases examined, the

TABLE 1.—Details of Experiment 89

Date and Time of Examination	Duration of Current in Seconds	Approximate Strength of Current in Volts	Faradism
6/28/20 Before operation	0.00015	..	+
45 minutes later	0.00015		
2½ hours later	0.00015	60	
4 hours later	0.00015		
9 hours later	0.00015		
24 hours later	0.00015	..	+
46 hours later	0.009	..	—
7/ 8/20	0.009	..	—
7/22/20	0.009	..	—
8/21/20	0.009	..	—
9/ 3/20	{0.0008	21	—
	}0.00066?	42	—
9/13/20	{Posterior muscles 0.00033	42	—
	}Anterior muscles 0.00015	42	—
9/20/20	{0.00033	22	?
	}0.00015	28	
10/11/20	0.00015	16	+ but very weak
10/18/20	0.00015	16	+ with good contractions

Summary: Left sciatic cut and normal nerve-muscle response for at least twenty-four hours and only muscle complex after forty-six hours. First nerve-muscle complex sixty-seven days after operation and duration of current gradually shortened to normal in thirty-eight days. Faradism was weakly present at this time, therefore chronomyometer test showed regeneration thirty-eight days ahead of faradism. Regeneration confirmed histologically.

TABLE 2.—Details of Experiment 91

Date and Time of Examination	Duration of Current in Seconds	Approximate Strength of Current in Volts	Faradism
6/28/20 Before operation	0.00015	57	+
½ hour after operation	0.00015	57	+
20 hours later	0.00015		
50 hours later	0.00015		
68 hours later	0.00015		
69 hours later	0.00015		
70 hours later	0.00015		
75 hours later	0.009		
7/ 8	0.009		
7/22	0.009	..	—
8/21	0.009		
9/ 3/20	0.009		
9/13	0.009	..	—
9/20	0.009	..	—
10/11	{0.00033 doubtful at	33	
	}0.00033 definite at	55	—
10/18	0.00015	42	—
10/26	0.00015	22	{± anterior muscles + posterior muscles
11/ 6	0.00015	14	+

Summary: Nerve-muscle complex lost between seventy to seventy-five hours began to return after from eighty-two to one hundred and two days and completely returned after one hundred and nine days, while faradism first returned after one hundred and seventeen days. Regeneration was confirmed microscopically.

protocols of only twenty-one are recorded as the others threw no light on this investigation. We record here only the positive findings in each of these cases.

A study of the twenty-one cases reported and Table 3 lead us to the following conclusions:

1. As regeneration occurs the long nerve-muscle complex appears first and as regeneration continues the nerve-muscle complex shortens until finally it reaches the value of a normal nerve-muscle complex. The early appearance of a long nerve-muscle complex enabled us to recognize that there was beginning regeneration. Thus an earlier diagnosis and an earlier favorable prognosis was possible. The ultimate recovery of all patients in whom this was observed has confirmed this opinion.

The minimum voltage necessary to cause contractions may remain practically the same at each test although the duration shortens, but in some instances it may vary considerably from time to time and this is due to the variation in tissue edema, temperature of the muscles, etc.

TABLE 3.—Time Chronomyometer Response Preceded Other Signs of Regeneration

Case No.	Diagnosis	Before Faradism	Before Voluntary Contractions	Before Decrease in Anesthesia	Remarks
1	Left sciatic paralysis..............	3 months	3 months	2 months	
2	Incomplete brachial plexus injury	3 months	3 months	5 months	
3	Right sciatic incomplete...........	4 months	2 months	2-4 months	
4	Left sciatic paralysis..............	6 months	1-2 months	No gain	
5	Poliomyelitis......................	Not tested	2 months		
6	Bell's palsy........................	No gain	23 days	....	No degeneration of nerve
7	Left facial paralysis..............	Not tested	1-3 months		
8	Left facial paralysis..............	1 month	23 days		
9	Bell's palsy........................	Not tested	1 week	....	No degeneration of nerve
10	Right facial paralysis....	Probably 3 months	Probably 3 months		
11	Left facial paralysis..............	Not tested	1 week	....	No degeneration of nerve
12	General polyneuritis...............	Faradism too painful			

In Table 3 it will be noted that the nerve-muscle complex returned from one to six months before faradism, one week to three months before voluntary contractions appeared and from zero to five months before anesthesia decreased. The greatest gain was observed in cases of injury to the long nerves and the least gain in the facial nerve lesions. This is, of course, to be expected for the distance the regenerating axis cylinders must grow and the size of the muscles innervated influences markedly the time between beginning and complete recovery. The time between degeneration and regeneration of the nerve determines to a large extent the amount of atrophy of the muscles, no matter how well they are cared for.

2. The nerve-muscle complex had disappeared by the fifth day in the posterior group of muscles in Case 3. This was the only case we saw

early enough to enable us to determine when the nerve-muscle complex first disappeared. This agrees with our animal experiments in which the nerve-muscle complex disappeared invariably at the end of seventy-six hours after complete severance of the nerve.

Adrian has reported a case of facial paralysis in which the nerve muscle chronaxie disappeared between the fifteenth and sixteenth day. This would indicate that in human nerves there is considerable variation as to when the nerve muscle complex is lost.

3. The presence of the nerve-muscle complex in cases in which there is no voluntary movement is a valuable prognostic sign as illustrated by Cases 6, 9 and 11. In these cases because of the normal nerve muscle complex we gave a good prognosis for early recovery. Therefore, whenever the nerve-muscle complex is present, even if there is no voluntary movement, no surgical interference should be considered.

4. Faradic response did not return until the nerve-muscle complex was 0.00033 second or shorter, that is, not until the irritability of the nervous tissue reached normal limits and voluntary movements were beginning to return. Case 12, in which hyperalgesia was present, illustrates strikingly the difficulty of testing with faradism on account of the pain, for even with weak currents the repeated stimulus is painful while a single shock of shorter duration is well tolerated by the patient.

5. Voluntary contractions returned at about the same time that faradism returned or when the nerve-muscle complex had reached normal limits.

6. The decrease in the area of anesthesia may occur parallel with the appearance and shortening of the nerve-muscle complex or it may lag considerably behind. In cases of motor nerve lesions, as in the facial, this part of the examination is, of course, useless, and conversely the electrical test at first seems to be useless in lesions of sensory nerves. That this is probably not true is suggested by Adrian's[14] work in which he determined the strength-duration curve for sensory nerves. This suggests the same possibilities for sensory nerves as we have found for motor nerves although we have made no observations on this point.

7. In incomplete nerve lesions, as in Case 3, in which only a few fibers remain intact, the detection of one muscle showing even the slowest nerve-muscle complex may be of great diagnostic and prognostic value. In this case it saved the patient an exploratory operation and recovery followed in due time.

8. In extensive lesions as those of a plexus, Case 2, or a high sciatic lesion, Case 17, the progressive lengthening of the nerve-muscle complex as one proceeds distally from the lesion may mean one of two things. If the case is seen early it means that the injury is incomplete,

while if the case is seen late it means either that the injury is incomplete or that regeneration has begun. The latter point is easily determined by a subsequent examination. In either case we feel that the prognosis is usually good and that operation is not indicated until it has been proved that regeneration is stationary after repeated examinations.

9. The only case of poliomyelitis cited, Case 5, shows a change from the muscle complex to the normal nerve-muscle complex in two months in some of the muscles, which we interpret as meaning that the anterior horn cells were regaining their activity. This method offers a possible means of determining with mathematical accuracy when the process of recovery in the affected nerves in poliomyelitis has come to a standstill.

10. When patients were seen a few months after injury and showed complete paralysis of a given nerve we delayed making a prognosis or stating whether operation was advisable until the axis cylinders might have had time to reach the nearest muscle distal to the lesion. We used as a basis for estimating when this time should be the measuring of distance from the lesion to the motor point of the nearest muscle. This distance in centimeters gives the number of weeks it should take the regenerating axis cylinders (if regenerating) to reach the nearest muscles and thus be detected by the electrical test. One cm. per week seems to be a conservative average rate of regeneration, but it must be used with judgment for each case varies and the entire picture must be considered. Cases 1 and 4 show the value of waiting in old cases. We feel, however, that a case seen early, unless the injury is only a few centimeters from a motor point, is entitled to an exploratory operation if no signs of recovery are present at the end of from six to eight weeks.

11. We have some evidence to indicate that there is some relation between the number of axis cylinders in a nerve and the length of the nerve-muscle complex. In Case 3 we were able to study the popliteal nerve in cross section and found that 5 cm. below the knee, axis cylinders were present in very large numbers (appeared like a normal nerve) while 5 cm. distally from that point the number of axis cylinders was definitely decreased. This decrease continued until at the ankle there were about one or two axis cylinders to a low power field. The electrical response of the gastrocnemius was shorter than that of the tibialis anticus, and as the former muscle gets its innervation higher up the variation in the length of the nerve-muscle complex may have been dependent on the number of axis cylinders present. It may of course be possible that the variation in the threshold duration necessary to produce a contraction accounts for the difference in electrical reaction at different stages of regeneration. Further observations are necessary to clear up this point.

CASE 1.—B. S., bullet wound in thigh January, 1920, tourniquet applied on lower third of thigh for two days to control hemorrhage, followed by paralysis of left leg.

TABLE 4.—FINDINGS IN CASE 1

Dates of Examinations	Motor Points Tested	Duration of Current in Seconds	Approximate Strength of Current in Volts	Type of Contraction	Voluntary Contractions	Anesthesia to Pin Prick	Remarks
7/10/20	All of left leg	0.009	85	Fair	None	That of sciatic lesion	Trophic ulcer of heel and great toe; massage and electricity started; impression-degeneration of sciatic nerve below thigh
	All of right leg and left thigh	0.00033	82	Good	Normal	None	
8/24/20	Soleus and median head of gastrocnemius	0.00066	90	Weak	None	Same as on 7/10	Muscles somewhat spastic; good prognosis given; faradism negative
	Tibialis anterior	0.0008	90	Weak	None	Same as on 7/10	
10/20/20	Soleus and median head of gastrocnemius	0.00033	105	Weak	None	To mid-leg lateral and below malleolus medial	Edema of leg, infection of toes; no massage for two months; faradism negative
	Tibialis anterior	0.00015	88	Weak	None		
11/30/20	Anterior and posterior muscles of left leg	0.00015	95	Fair	Slight	Sole of foot and one inch up all around foot	Faradism weak; infection improving

Summary—Diagnosis: Complete degeneration of sciatic nerve below thigh but prognosis delayed to allow regenerating fibers (if present) to reach muscles and skin of leg. Eight months after injury long nerve-muscle complex first appeared and good prognosis given. Three months later nerve-muscle complex was normal, slight voluntary movements were present and anesthesia was greatly reduced. Gain of three months over voluntary movements and faradism and two months over sensory. (In another similar sciatic lesion the sensory paralleled the nerve-muscle response.)

Case 2.—H., brachial plexus injury received November, 1919, explored January, 1920—all roots intact, but three were thinned and part of one excised and end to end suture done (left arm). Massage and electricity given throughout course.

TABLE 5.—Findings in Case 2

Dates of Examinations	Motor Points Tested	Duration of Current in Seconds	Approximate Strength of Current in Volts	Type of Contraction	Voluntary Contractions	Anesthesia to Pin Prick	Remarks
4/23/20	Biceps brachii	0.00033	75	Fair	None	Up to just above elbow posterior and about 6 cm. anterior; sensation of current and muscle contractions present down to elbow	Because of progressive shortening of current duration as arm was ascended a good prognosis given; no reaction to faradism below shoulder
	Teres major	0.00033	75	Fair	None		
	Median nerve	0.00065	75	Fair			
	Ulnar nerve	0.00065	75	Fair			
	Flexor carpi radialis	0.009	75	Good	None		
	Extensor indicis proprius and muscles of hand	0.009	75	Fair	None		
5/13/20	Biceps	0.00033	72	As before	As before	As before	Faradism negative in all
	Ulnar nerve	0.00065	75				
	Median nerve	0.00065	75				
	Flexor carpi radialis	0.009	75				
	Extensor indicis proprius and muscles of hand	0.009	75				
6/16/20	Biceps	0.00015	70	Poor	As before	As before	Faradism negative in all
	Median nerve	0.00033	75	Poor			
	Ulnar nerve	0.00033	75	Fair			
	Flexor carpi radialis	0.009	75	Good			
	Extensor indicis proprius and muscles of hand	0.009	75	Fair			
7/20/20	Biceps	0.00015	75	All stronger than on 6/16/20	Slight contractions of muscles above elbow	As before	Faradism positive in biceps, triceps and brachialis; negative in all others
	Triceps	0.00015	75				
	Brachialis	0.00015	75				
	Ulnar	0.00033	75				
	Flexor carpi radialis	{0.009 {0.0008 doubtful	75				
	Extensor indicis proprius and muscles of hand	0.009	75				
9/28/20	Biceps	0.00015	85	More active than on 7/20/20	Very slight flexion of elbow and supination; movements of shoulder girdle active	As before but pinching is felt numbly over entire lateral surface of forearm and hand but not on median surface	
	Triceps	0.00015	85				
	Brachialis	0.00015	85				
	Ulnar	0.00015	75				
	Flexor carpi radialis	0.00080	85				
	Extensor indicis proprius and extensors of wrist	0.00080	85				
	Flexor of wrist	0.00080	85				
	Muscles of hand	0.009	55				
11/30/20	Biceps, triceps, brachialis, ulnar	0.00015	85	Fair	Supination, pronation, flexion and extension of elbow abduction of arm weak but definite	As on 9/28/20 except anesthesia to just below elbow and pinching felt numbly over all of forearm and hand and first phalanx of fingers	
	Extensors of wrist	0.00080	92	Fair			
	Flexor carpi radialis and flexor of wrist	0.0008	92	Fair			
	Muscles of hand	0.009	92	Fair			
3/16/21	Biceps, triceps, brachialis and ulnar	0.00015	85	Good	As on 11/30 but much stronger; very slight flexion of fingers	From middle of hands distal; from elbow and midarm-medial down cannot distinguish between head and point of pin; deep muscle and joint sense corresponds in quality to above	Shoulder, elbow, wrist and finger joints show from 20-40% restriction of motion; atrophy of muscles of hand and forearm more marked since patient has not had treatment past 2 months; faradism as on 7/20/20
	Extensors of wrist	0.0008	100	Only fair			
	Flexor carpi radialis	0.0008	100	Only fair			
	Flexors of wrist	0.0008	100	Only fair			
	Muscles of hand	0.009	75	Only fair			

Summary: Shows a progressive lengthening of the minimum duration of current; therefore good prognosis given; a slow change of muscle complex to nerve-muscle complex in many muscles and a shortening of nerve-muscle complex in others; a return of voluntary movement in those muscles whose complex shortened to normal; a reduction in anesthesia; a gain with the chronomyometer of 3 months over faradism, 3 months over voluntary movements and 5 months over reduction of anesthesia.

Case 3.—N. K., popliteal aneurysm ligated in upper part of popliteal space, June 6, 1920.

TABLE 6.—Findings in Case 3

Dates of Examinations	Motor Points Tested	Duration of Current in Seconds	Approximate Strength of Current in Volts	Type of Contraction	Voluntary Contractions	Anesthesia to Pin Prick	Remarks
6/ 3/20	Right leg; all points	Infinite	70	None	None	Lower lateral surface of leg	No contractility or irritability of muscle—ischemid probably
	Right thigh and left leg	0.00033	50	Good	Normal	Decrease over balance	
6/ 7/20	Tibialis anticus	0.0008	70	Fair	None	That of sciatic nerve paralysis	Faradism negative
	All other on right leg	0.009	70	Fair	None		
6/15/20	All in right leg	Same on 6/7/20	...	...	...	...	Faradism negative
8/13/20	All in right leg	0.0008	70	Fair	None	Same as 6/7/20 practically	Faradism negative
10/16/20	Right leg and anterior group	0.0006 definite; 0.00033 doubtful	105	Good	Slight	Foot and ankle	Trophic ulcer on heel; patient has very acute purulent arthritis of right knee; faradism positive; some edema
	Posterior group (right leg)	0.00033	105	Good	Slight		
10/23/20	...	...	...	...	...	...	Midthigh amputation right and nerve from knee to ankle studied histologically

Summary: Nerve-muscle complex returned 4 months ahead of faradism, between 2-4 months before sensory anesthesia decreased, and 2 months before voluntary contractions. On June 3, 1920, a diagnosis of ischemic paralysis was made but on June 7, 1920, it was clearly that of sciatic paralysis (incomplete). A good prognosis was given. The length of the nerve-muscle complex gradually shortened until 4 months later when it was within normal limits for the muscles of the leg and slight voluntary contractions were present; those of foot not tested. Histologically, cross sections of tibial nerve showed approximately normal number of axis cylinders 5 cm. below knee, fewer 10 cm. below knee and so on until at ankle there was about one to a low power field. This checks up with the electrical findings.

Case 4.—G. B., fracture of distal end of left femur on March 21, 1920.

TABLE 7.—Findings in Case 4

Dates of Examinations	Motor Points Tested	Duration of Current in Seconds	Approximate Strength of Current in Volts	Type of Contraction	Voluntary Contractions	Anesthesia to Pin Prick	Remarks
6/23/20	All left leg....................	0.009	70	Fair	None in foot	That of a sciatic lesion............	Impression-degeneration of sciatic nerve below popliteal space; massage and electricity and wait 2 months
	All left thigh................	0.00033	70	Very active	Normal	None	
7/26/20	All of left leg................	0.009	105	Weak	None	Same	No massage or electricity for 2 weeks, therefore much edema; faradism negative
8/26/20	Left tibialis anticus, peroneus	{0.0008 sure {0.0006 doubtful	75	Weak	None	Smaller but of same shape as on 6/23	Prognosis given, good and no operation advised; faradism negative
	Gastrocnemius and soleus...	0.0008	75	Weak	None		
9/18/20	All of left leg................	{0.00033 {0.009	100 40	Fair	Very slight if any	Sole of foot and about 1½ inches up on foot all around	Few trophic ulcers; faradism negative
11/17/20	All of left leg................	0.00015	90	Fair	Contraction of muscles but ankylosis prevents movements	Over all of toes and distal half of sole	Faradism negative (cyanosis of leg below knee after baking); patient could not stand strong enough faradism to cause contractions
2/ 2/21	All of left leg................	0.00015	90	Good	Good contractions	Over all of toes with blisters and cyanosis	Faradism positive

Summary: Muscle complex changed to the longest nerve-muscle complex in 2 months after first examination and this shortened to normal in 3 months; area of anesthesia became smaller parallel to decrease in duration of current but both showed regeneration from 1 to 2 months before voluntary contractions. When patient was first seen a complete sciatic paralysis was diagnosed, but the progn osis was withheld for 2 months (5 months after injury) to allow regenerating fibers (if present) to reach the muscles and skin of the leg, At the end of this time the anesthesia had decreased and duration of current showed a long nerve-muscle complex; therefore a good prognosis was given without an exploratory operation. This prognosis was followed by loss of anesthesia, normal nerve-muscle complex and voluntary contractions 3 months later at which time the patient could not stand a strong enough faradic current to cause contractions (gain over faradism of at least 3 months, over voluntary movements at least 23 days). On September 18 response to 0.00033 second at 100 V and 0.009 second at 40 V. 40 V = 2 × rheobasic voltage.

Case 5.—P. G., poliomyelitis of one and one half years' duration; baking and massage past six months; right leg, poor flexion of foot, slight extension of big toe, poor extension of thigh, inversion and eversion of foot gone, flexion of knee gone.

TABLE 8.—Findings in Case 5

Dates of Examinations	Motor Points Tested	Duration of Current in Seconds	Approximate Strength of Current in Volts	Type of Contractions	Voluntary Contractions
6/26/20	Gluteus maximus	0.00065	95	Fair	?
	Biceps femoris long head	0.009	95	Fair	No
	Semitendinous	0.009	95	Fair	No
	Semimembranous	0.009	95	Fair	No
	Gastrocnemius	0.0008	95	Fair	No
	Soleus	0.0008	95	Fair	No
	Vastus lateralis	0.00015-33	95	Fair	Yes
	Vastus medialis	0.00015-33	95	Fair	Yes
	Rectus femoris	0.00015-33	95	Fair	Yes
	Tibialis anticus	0.009	95	Fair	No
	Extensor hallicus longus	0.009	95	Fair	No
	Peronei	0.0008	95	Fair	Slight
8/ 3/20	Gluteus maximus	0.00015	95	Fair	Slight
	Biceps femoris	0.00015	95	Fair	Slight
	Semimembranous	0.00015	95	Fair	Slight
	Semitendenous	0.00015	95	Fair	Slight
	All others as on 6/26				

Summary: The muscle and slow nerve-muscle complexes explain the losses or impaired function of various muscles; by referring back to the origin of the nerves supplying the affected muscles the lesion is in L 4 and 5, S 1, 2 and 3 segments of the cord; muscles of thigh changed from muscle to rapid nerve-muscle complexes as slight voluntary movements returned.

Case 6.—F., Bell's palsy left—onset July 30.

TABLE 9.—Findings in Case 6

Dates of Examinations	Motor Points Tested	Duration of Current in Seconds	Approximate Strength of Current in Volts	Type of Contraction	Voluntary Contractions	Remarks
8/ 2/20	All of right and left facial	0.00015	50	Good	None on left	Faradism present
8/ 4/20	All of left facial	0.00015	50	Good	None on left	Faradism present
8/ 9/20	All of left facial	0.00015	50	Good	None on left	Faradism present
8/25/20	All of left facial	0.00015	50	Good	Slight	Faradism present
10/15/20	All of left facial	0.00015	50	Good	Good	Faradism present

Summary: Paralysis came on over night, nerve-muscle response to both chronomyometer and faradic tests at all times but voluntary movement did not return for over three weeks. Good prognosis given on first examination. Voluntary contractions returned slightly in three weeks, definitely in six weeks.

Case 7.—M. W., left facial paralysis, complete, following suppurative parotiditis and open drainage Nov. 4, 1920. Paralysis first noted December 7.

Case 8.—R. T., left facial paralysis, onset July 2, 1920.

Case 9.—H. R., right facial paralysis; onset sudden, July 15, 1920; examined July 24, 1920; slight voluntary power in orbicularis oculi only; nerve-muscle response 0.00015 second with good contractions over entire right and left face; given good prognosis for early recovery possibly within two weeks. Aug. 3, 1920, (ten days later) a letter from the patient stated that he had the normal use of all muscles of the face. He was not tested with faradism which test no doubt would have been positive.

TABLE 10.—Findings in Case 7

Dates of Examinations	Motor Points Tested	Duration of Current in Seconds	Approximate Strength of Current in Volts	Type of Contraction	Voluntary Contractions	Remarks
1/ 5/21	All of left facial:					
	Upper branch..	0.009	90	Weak	None	
	Mid branch................	{0.0008	90	Weak	None	
		{0.009	30			
	Inferior branch............	0.00015	30	Fair	Partial	
1/18/21	Upper branch..............	0.009	30	Weak	None	Patient massaging own face
	Mid branch................	0.0008	90	Weak	None	
	Inferior branch............	0.00015	30	Fair	Partial	
2/ 2/21	Upper branch..............	....	..	......	None	Patient massaging own face
	Mid branch................	....	..	......	Slight	
	Inferior branch............	....	..	......	Fair	
2/28/21	Upper branch..............	0.0008	80	Weak	None	Patient massaging own face
	Mid branch................	0.00033	80	Weak	Fair	
	Inferior branch............	0.00015	30	Weak	Good	
4/15/21	Upper branch..............	0.00025	50	Weak	Slight	Patient massaging own face
	Mid branch................	0.00011	30	Good	Fair	
	Inferior branch............	0.00011	30	Good	Good	

Summary: Seen four weeks after paralysis noted; very slight voluntary control of muscles innervated by inferior branch. Good prognosis given on basis of good nerve-muscle complex in inferior branch and slow in mid branch, two weeks later some muscles in superior branch showed nerve muscle complex and two weeks after this the patient had some voluntary control of muscles innervated by lower two branches. Two months later there was rapid nerve muscle complex in all three branches and voluntary control in all three branches, though that in the superior branch was slight.

TABLE 11.—Findings in Case 8

Dates of Examinations	Motor Points Tested	Duration of Current in Seconds	Approximate Strength of Current in Volts	Type of Contraction	Voluntary Contractions	Anesthesia to Pin-Prick	Remarks
7/23/20	All of left facial	0.009	20	Fair	Negative	None	Faradism negative
8/10/20	All of left facial	0.009	20	Fair	Negative	None	Faradism negative
8/28/20	All of left facial	0.0008	55	Fair	Negative	None	Faradism negative
9/20/20	All of left facial	0.00015	15	Fair	Very doubtful	None	Faradism positive; slight wrinkles left side of face
10/23/20	All of left facial	0.00015	15	Good	Present but weak	None	Faradism positive
11/15/20	....	... ...	..	......	Practically normal		

Summary: Patient seen three weeks after paralysis, etiology unknown but possibility of severed nerve trunk very remote; operation not warranted though no nerve-muscle complex present. Prognosis withheld until August 28, two months from onset, when beginning nerve-muscle complex developed, yet faradism negative. Faradism positive one month later when doubtful voluntary contractions were present and wrinkles of skin began to return. Gain over faradism one month, over voluntary contractions at least twenty-three days.

Summary: This case illustrates that normal nerve-muscle complex was present even when the muscles did not contract voluntarily and recovery was rapid.

Case 10.—V. H., there was right facial paralysis in April, 1920, following a mastoid operation. Examination was made Oct. 21, 1920; paresis of middle and inferior branches and complete paralysis of superior branch; nerve-muscle complex of inferior and middle branches, 0.00015 second, superior branch 0.009 second with 50 volts and 0.008 with 70 volts; faradism positive in inferior and middle branches, but negative in the superior. Jan. 29, 1921, the patient's letter stated that he had good voluntary movement over the middle and inferior branches, but slight in superior branches.

Summary: Because of beginning nerve-muscle complex with 70 volts, we felt entire nerve would recover, and the later report seems to indicate that it is occurring.

Case 11.—H., partial left facial paralysis following brain abscess of left temporal lobe on Dec. 1, 1920. Paralysis noted Jan. 8, 1921. Examined Jan. 13, 1921. Only slight voluntary control of upper branch; no voluntary control of the two lower branches; good reaction in all the branches with 0.00015 at 10 volts; Jan. 8, 1921, good voluntary control of all branches.

Summary: Rapid nerve-muscle complex was present at height of paralysis, so that good prognosis was given and complete recovery followed in a week.

Case 12.—G. B., general polyneuritis (?), examined Nov. 20, 1920; all voluntary movements of left leg and ankle gone and only slight movement of third toe. Anterior and posterior groups of muscles of the left leg reacted only at 0.009 second with 80 volts. Right leg, movements of ankle and toes were slightly present and muscles reacted to 0.00033 second with 95 volts. No contractions elicited in either leg with faradic or galvanic current because the hyperalgesia made it too painful to use a strong enough current to bring out a reaction with either current. Burning sensation which patient could stand comfortably was present with the chronomyometer tests.

Summary: The chronomyometer reactions corresponded to the paralysis or paresis present. This case illustrates that electrical tests may be made on a patient with the chronomyometer when it is not possible to test the patient by ordinary methods because they are too painful.

Case 13.—E. K., median and ulnar secondary suture; extensor digitorum communis, 0.00015 second and good voluntary power; extensor carpi ulnaris 0.00033 second and poor voluntary power; other muscles of the forearm were normal. Ten months later, 0.00015 second in all muscles of the forearm and hand at 25 volts except lumbricales, which required 95 volts and good voluntary power in all muscles except the lumbricales.

Summary: This case illustrates the increase in voluntary power paralleled by shortening of the nerve-muscle complex.

Case 14.—A. W. G., gunshot wound through the lumbar region. Current strength 65 volts, right leg: obturator nerve, 0.00033 second; femoral nerve, 0.00015 second; biceps muscle, 0.00033 second; tibial nerve, 0.00033 second; peroneal nerve, no response; tibialis anticus muscle, 0.009 second; peroneii, 0.009 second; soleus, 0.00015 second; gastrocnemius, 0.00015 second. Left leg: sciatic nerve, 0.00015 second; peroneal nerve, negative; tibial nerve, 0.00015 second; biceps femoris, 0.00015 second; tibialis anticus, 0.0008 second; peroneii, 0.0008 second.

Summary: Examination revealed a bilateral injury to the sacral plexus affecting the roots which supply primarily the peroneal nerves, especially on the right side.

Case 15.—A. G., median and partial ulnar in axilla; repaired two years ago. Examined June 30, 1920. All motor points 0.00015 second with 70 volts and limited function, but sensory regeneration practically normal; on Feb. 20, 1921, practically normal function.

Summary: Rapid nerve-muscle complex indicated that problem of regaining function was one of reeducation which was confirmed by observation eight months later.

Case 16.—D. L. R., ulnar injury above the wrist six years ago; repaired March, 1920; tested July 9, 1920; some sensations in little finger. There was marked atrophy of muscles of hand, therefore electrical testing was difficult. Reaction to 0.0008 second and doubtful voluntary movements of ulnar muscles.

Case 17.—M. R., examined July 20, 1920; reduced congenital dislocated hip with sciatic nerve injury left; reduced three years ago, in cast three months, anesthesia from knee down, weak movements of knee and paralysis of foot when cast was removed. Reaction of gluteals, 0.00015 second; upper thigh, 0.00033; lower thigh, 0.00065; below the knee, 0.0008 second posteriorly, and 0.009 anteriorly. Right leg showed normal reaction. March 19, 1921: All of left thigh, 0.00015 second, soleus and gastrocnemius, 0.0008 second, tibialis anticus and peroneii, 0.009 second with poor reaction, plantaris longus, 0.009 second. Anesthesia to pin prick below ankle, but deep sensation present down to tips of toes. Voluntary Movements: Thigh good, knee fair, ankle only slight extension, foot inverted with toe drop.

Summary: In eight months nerve-muscle complex of thigh shortened, and parellel with this the voluntary power increased; no signs of improvement below the knee except a decrease in the anesthesia and a slight extension of the ankle which shows that the slow nerve-muscle complex means some innervation.

Case 18.—S., spastic paraplegia from a spinal cord cyst. Reaction of all motor points of both legs, 0.00015 second with 20 volts.

Summary: This case shows that the paralysis due to injury of the upper neuron did not alter the electrical reactions of the lower neuron.

Case 19.—J. B., back injured July 20, 1920. Tested Sept. 10, 1920. Paraplegia from the level of iliac spines down, with anesthesia to touch, and only the muscle complex 0.009 with 100 volts.

Summary: Complete degeneration of the lower cord and peripheral nerves.

Case 20.—R. K., amyotonia congenitalis (?). No nerve-muscle or muscle response in either leg except in the rectus femoris right (0.00015 second, good response); sartorius right (0.00015 second, fair response) vastus externus, right (0.0008 second, weak response). Voluntary movements only in rectus femoris and sartorius. No anesthesia or trophic changes. Legs about half normal size, but had appearance of having normal sized muscle for that sized leg.

Summary: The electrical response was parellel to voluntary movements and showed a degeneration of the motor nerves and their muscles.

Case 21.—M., lower spinal injury followed immediately by operation; complete paralysis of both legs since accident one and one-half years ago; marked atrophy of muscles of both legs; no voluntary movements; trophic ulcers and limitation of motion of joints of both legs, no muscle or nerve-muscle response in either leg; anesthesia up to mid-thigh. The patient showed complete loss of irritable nerves or muscles eighteen months after injury.

DISCUSSION

Previous workers who have studied regeneration of nerves by observations on the chronaxie have hoped to find a method by which at a single examination it could be determined that the process of regeneration was going on. In consequence Adrian [14] has arrived at the conclusion that though chronaxie is of great physiologic interest, it has no practical value. Thus he says "The presence or absence of excitable nerve fibers can be detected well enough by the ordinary faradic coil and except for purposes of research there is little to be gained by the use of condensers or any other more elaborate method." In Lapicque's [13] published papers he has observed that chronaxie lengthens as degeneration progresses, but we find no statement indicating that he ever studied chronaxie changes in regenerating nerves. Furthermore, in all his studies he seems to disregard the variation in the strength of the current necessary to bring out chronaxie.

In the work recorded in this paper repeated observations were made with the chronomyometer during the regeneration and degeneration of nerves. Thus it has been possible to show that the nerve-muscle complex becomes shorter during the period of regeneration and that it lengthens during the degeneration of a nerve.

The only instance of repeated observations of chronaxie that we have been able to find any record of is a single case of Adrian's [14] on a facial paralysis in which he made observations on the orbicularis oculi and observed a gradual shortening of the chronaxie from 0.0075 second to 0.0003 second. In other words, the chronaxie shortened about twenty times, yet Adrian does not seem to consider this observation at all significant. Possibly this was due to the fact that voluntary movement was present when the chronaxie was 0.0075 second. In our own observations we have shown that far more important than chronaxie are the changes in the minimum duration of the current in so far as it brings out the progressive shortening of the nerve-muscle complex that occurs when a nerve regenerates.

It is, of course, apparent that until a regenerating nerve has reached a muscle one cannot hope to detect any changes in the minimum duration of the current. Thus the time between the appearance of the muscle complex following a nerve injury and the reappearance of the nerve-muscle complex will vary with the distance between the site of the nerve injury and the nearest muscle to be innervated by the nerve under consideration. When a nerve injury case is seen early (after about three weeks) it is of great value to know whether only the muscle complex is present, for this would indicate that the nerve has completely degenerated; following this, however, no observations on minimum duration are of value until the nerve has reached the nearest muscle. When a nerve, therefore, has a great distance to grow, which would mean months before one could hope to get any evidence of beginning regeneration, an early exploration seems desirable, but if the nerve has only a short distance to grow to the nearest muscle, exploration might well be deferred until the average time for regeneration has elapsed (about 1 cm. a week). Where the principal disability is due to atrophy of small muscles, as in an ulnar or musculospiral paralysis, it may be unwise to defer operation.

If at exploration the nature of the lesion is still uncertain, another method suggested by one of us (J. Y. M.) of determining whether the axis cylinders have grown through the lesion may be employed. This subject was discussed in another paper which appeared in the November issue of *Archives of Surgery.*

SUMMARY AND CONCLUSIONS

The following points seem to us to be the most important ones derived from this study:

1. The chronomyometer is a practical instrument for detecting regeneration of nerves in clinical cases.

2. The determination of the minimum duration of a current necessary to stimulate a muscle is of greater value than determining the chronaxie.

3. The nerve-muscle complex after a nerve has been cut has always disappeared in animals within seventy-six hours and in one human case by the fifth day.

4. As regeneration occurs the nerve-muscle complex shortens gradually. This has been demonstrated both in animal experiments and clinical cases.

5. The nerve-muscle complex begins to appear from one to six months before faradic response, from one week to three months before voluntary contractions and from zero to five months before contraction of the area of anesthesia.

6. The variation in the minimum duration of the current necessary to stimulate muscles along the distribution of a nerve as well as repeated tests of one muscle may be of value in determining the regeneration of a nerve.

7. The faradic response of muscles and voluntary movements do not return until the nerve-muscle complex has reached normal limits.

8. Chronomyometer tests are of value as soon as a nerve has degenerated (five days or less) and as soon as regenerating fibers have reached the nearest muscle. This time can be estimated with fair accuracy by measuring the distance between the lesion and the nearest motor point.

9. The method herein described offers a more accurate means of determining much earlier the progress of nerve regeneration. Combined with a study of sensory changes, trophic disturbances, etc., it is a distinct aid in the prognosis and treatment of nerve injuries.

DISCUSSION

Dr. Sanger Brown of Kenilworth said that in the early eighties of the last century it was rather enthusiastically taught in some quarters that electricity might be used in paralysis due to a nerve lesion to hasten recovery, and no doubt at the present time it is quite extensively used for this purpose. Since these reported investigations seem to have been carried out with such exceptional thoroughness, he would like to ask whether the writers of the paper had any suggestions to offer on this point. He also asked whether the methods employed in testing would have any injurious effect on nerve lesion at any stage, because no matter how absurd such a question might appear, it was likely to be raised in medicolegal cases, where such tests were used.

Dr. M. Allen Starr of New York thought that the value of Dr. Sachs' paper could not be emphasized too greatly, because it had a medicolegal application. He said that occasionally he was asked to decide cases before the New York State Commission for Compensation for Injuries, and he recalled a case seen recently in which this would have decided definitely whether the man was going to recover from a serious brachial palsy or whether he was permanently disabled.

Dr. Isador Abrahamson, New York, asked whether Dr. Sachs, with his newer method of examination had studied its relationship to the incidence of such sequelae of facial palsy as contracture and hemispasms.

Dr. Ernest Sachs of St. Louis, in closing, said regarding the therapeutic effect, that this method had been of distinct value. A woman, who had a gash across her face, with complete facial paralysis, went to see him. The question was whether or not the facial nerves had been cut. Heretofore the only method of determining this was to wait and see whether the nerves would recover. By testing with this method, however, they found that the long nerve muscle complex was present. She was given a good prognosis, and in four months began to move her face.

They have tested now about thirty-five clinical cases of all sorts, and they have found that when the first evidence of the nerve muscle complex appearing is obtained, a complete regeneration of the nerve is certain.

Regarding Dr. Abrahamson's question about facial spasm, Dr. Sachs said they had had no experience with this condition.