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REPETITIVE STIMULATION BY COMMUTATOR AND CONDENSER.

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In all experiments made during the last few years on the heat production of nerve, and in recent experiments by Hill [1934] and by Scott [1934] on the time relations of excitation during repetitive stimulation, the stimulus has been a series of condenser discharges (one-way or alternating) provided by a condenser C (Fig. 1) connected to a revolving commutator and a battery. By means of this, all the pertinent characteristics of a stimulus can be controlled, namely:

(*a*) Frequency of shocks.
(*b*) Intensity (voltage) of each shock.
(*c*) Duration ("discharge time") of each shock.

By "discharge time" is meant RC, C being the capacity (in farads) of the condenser, and R the resistance in ohms of the discharge circuit. RC is the time in seconds for discharge to $1/e$ of the original charge, e being the base of the Napierian logarithms, the inductance of the circuit being neglected.

The commutator ring A has been of three different types:

(*a*) Containing a single pair of segments as in the revolving commutator listed by Messrs W. G. Pye; a similar ring was made for Mr Scott by Messrs C. F. Palmer.

(*b*) Containing four pairs of triangular segments, to allow the duration of contact to be varied (without variation of frequency) by moving the central brush a sideways.

(*c*) Containing a large number of segments (*e.g.* 40 or 46); this type of ring is of the ordinary commercial pattern, built up of copper segments with mica insulation. The ring itself can be obtained from Messrs Samuel Baxter of London, the complete commutator from Messrs C. F. Palmer.

The ring is mounted with a flywheel B on a shaft which revolves in ball-bearings. A worm W on the shaft drives the wheel D which rings a bell once in every 100 revolutions of the commutator: by this the speed can be measured with a stop-watch. By pulleys, a countershaft and a motor any desired speed can be obtained. In type (c) the even segments are joined together in parallel by soldered wires to an insulated brass

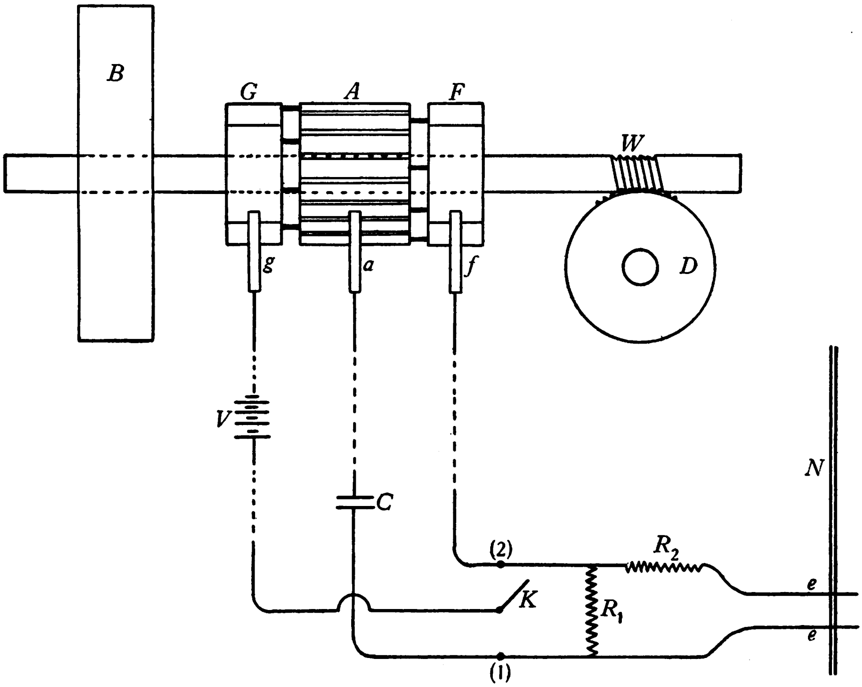

Fig. 1. **Revolving commutator with condenser, battery and resistances for nerve, or muscle, stimulation. A, commutator ring on shaft, with segments connected alternately to brass rings F and G carried on insulating brushes on the same shaft. B, flywheel. W, worm, driving toothed wheel D, which rings a bell every 100 revolutions of commutator. Shaft mounted on ball-bearings. f, g, a, insulated brushes of thin phosphor-bronze or copper strip, making contact with brass rings and commutator respectively, so that a is connected alternately to f and g. V, battery. C, condenser. N, nerve lying on electrodes e, e. R_1, shunt; R_2, series resistance. K, key for connecting to (1) for one-way shocks, to (2) for alternating shocks.**

ring F mounted on the shaft to the right of the commutator; the odd segments to a similar ring G on the left of the commutator. Three insulated phosphor-bronze or copper brushes, a, f, g, make contact with the commutator and the two rings, so that the middle brush is put into electrical connection alternately with the other two. With the connections shown in Fig. 1 and the throw-over key K connected to (1), a nerve can be stimulated with a series of condenser discharges all in one direction ("one-way"); or, by turning the key K over to (2), with a series of charges and discharges alternating in direction ("alternating").

To insure that no sparking occurs at the higher potentials as the brush passes from one segment to the next, the insulation should be rather wide. With types (*a*) and (*b*) there is no difficulty; with type (*c*) it is necessary to insist that the mica insulation should be at least 1·3 mm. across. When the commercial rings (*c*) are new the insulation resistance between the opposing systems of segments is apt to be rather low, perhaps owing to moisture in the dielectric; with time and use, however, a great improvement occurs, and the insulation resistance between F and G rises to hundreds of megohms.

The stimulator has generally been used with sensitive electrical recording apparatus, and it has been found best to remove the commutator and its motor some distance from the rest. The broken lines in Fig. 1 represent several metres of wire, flexible or lead-covered cable, connecting the commutator to the experimental table. The lead cover, when used with neurothermic apparatus, was earthed to avoid electrostatic disturbances.

With a 46-segment commutator (type (*c*)) the frequency can be varied as desired up to about 2500 one-way shocks per sec., or up to 5000 alternating shocks per sec. With low frequencies it is better (see below) to use a ring with a smaller number of segments, in which, for a given frequency, the linear speed is greater. The shocks can be varied in intensity by adjusting the voltage V; they can be varied in discharge time RC by altering either the capacity C or the discharge resistance R of the circuit. It is convenient to have a small box containing a few non-inductive resistances so as to vary R_1 and R_2 (Fig. 1) by switches as required. The stimulating efficacy of a shock is defined when we know the voltage, V, from which it is discharged, and its discharge time RC, assuming that there is no inductance in the discharge circuit. If $RC = 10^{-6}$ the discharge time is 1 microsecond; if $RC = 10^{-3}$ the discharge time is 1σ, or 1 millisecond.

The arrangement used for defining the discharge resistance R is similar to that employed by Lapicque [1926] and is shown in Fig. 1. The nerve of resistance N rests on electrodes e, e. For these it is best to use calomel half-cells, which are reliable and non-polarizable, with suitable connections moistened with Ringer's fluid. In series with the nerve is a resistance R_2, made up of a non-inductive resistance and the calomel cells. Shunting (R_2+N) is a resistance R_1. Then

$$R = R_1\left(1 - \frac{R_1}{R_1 + R_2 + N}\right).$$

If (R_1+R_2+N) is made large compared with R_1, *e.g.* 50,000 ohms as compared with 100, R is effectively R_1 and is known; or alternatively (R_2+N) can be directly determined; even an approximate determination is sufficient, provided that (R_2+N) is large compared with R_1.

There were several possible difficulties, or sources of error, in the use of this arrangement: (*a*) there might be sufficient inductance in the circuit to prevent the discharge of the condenser from following a simple exponential course, in that case the discharge would be slower than supposed; (*b*) the lines themselves, or the commutator, might have appreciable capacity; (*c*) with small capacities there might be appreciable leakage in commutator or lines, in the intervals between contact on alternate segments; and (*d*) with very rapid discharges the contact between the brush and the segments of the commutator might provide a resistance large enough to affect the time relations of discharge, and so give shocks which were different from those calculated from capacity and resistance. We will consider these possibilities separately.

(*a*) *Inductance of circuit.* In a circuit with inductance L henrys and capacity C farads the periodic time of oscillation is $2\pi\sqrt{LC}$ sec. If there be a resistance in the circuit the periodic time becomes rather greater, until the oscillation becomes critically damped when $R^2=4L/C$. If the discharge is effectively to follow the simple exponential relation, the resistance must be so great, or the inductance so small, that R^2 is sufficiently large compared with $4L/C$. In practice, in the present connection, it will be sufficient if R is three times as great as $2\sqrt{L/C}$.

It can be shown that the discharge of a condenser of capacity C through a resistance R of inductance L follows the equation

$$Q/Q_0=\frac{1}{2}\left(1+\frac{\mu}{\sqrt{\mu^2-1}}\right)e^{-\frac{t}{RC}(2\mu^2-2\mu\sqrt{\mu^2-1})}-\frac{1}{2}\left(\frac{\mu}{\sqrt{\mu^2-1}}-1\right)e^{-\frac{t}{RC}(2\mu^2+2\mu\sqrt{\mu^2-1})},$$

where $\mu=R/R_0$, R_0 being the resistance for critical damping, viz. $2\sqrt{L/C}$.

When μ is large, this becomes $Q/Q_0=e^{-t/RC}$.

For other values of μ the equation becomes:

$$\mu=2,\ Q/Q_0=1{\cdot}077e^{-1{\cdot}072t/RC}-0{\cdot}0773e^{-14{\cdot}93t/RC},$$
$$\mu=3,\ Q/Q_0=1{\cdot}030e^{-1{\cdot}030t/RC}-0{\cdot}030e^{-35{\cdot}0t/RC},$$
$$\mu=5,\ Q/Q_0=1{\cdot}010e^{-1{\cdot}010t/RC}-0{\cdot}010e^{-99t/RC},$$
$$\mu=7,\ Q/Q_0=1{\cdot}005e^{-1{\cdot}005t/RC}-0{\cdot}005e^{-195t/RC}.$$

Except for very short times, *i.e.* short compared with RC, if $\mu=3$ or more,

(i) the second term is negligible: thus for $t/RC=0{\cdot}2$ and $\mu=3$, the second term is only 0·00003;

(ii) the first term is nearly equal to $e^{-t/RC}$: thus for $t/RC=0{\cdot}2$, $e^{-t/RC}=0{\cdot}819$, for $t/RC=0{\cdot}5$, $e^{-t/RC}=0{\cdot}606$; for $\mu=3$ and these times the first term is, respectively, 0·838 and 0·615; for $\mu=5$, respectively, 0·825 and 0·609.

Thus, provided that μ = at least 3, and preferably 5, the discharge is practically unaffected by the inductance.

When the arrangement is used for very short discharge times it is necessary to insure that L, the inductance, is small enough. The inductance can be found at the same time as the extra capacity of the lines, with the commutator and its accessories arranged for nerve stimulation, by the method described in the next section. The circuit employed for one-way discharges in the neurothermic experiments had an inductance of about 8 microhenrys: that used by Mr D. Scott in his recent work on the time relations of repetitive stimulation [1934] had an inductance of about 11 microhenrys. Knowing the inductance we can calculate the resistance necessary to insure exponential discharge of the type $e^{-t/RC}$. It was shown above that R must be at least three times the critical value, namely, $2\sqrt{L/C}$; expressed in another way R must be at least 36 L/RC. Now RC is the discharge time. Assume a discharge time of 10^{-5} sec. and let $L=11\times10^{-6}$: then R must be at least 40. Assume a discharge time of 10^{-6} and the same value of L: then R must be at least 400. With $R=400$ and $RC=10^{-6}$ the capacity is 0·0025 microfarad. This is a practicable value, as is seen in the next section, so that discharge times down to a millionth of a second can safely be used.

For longer discharge times there is no difficulty. For shorter ones it is necessary to avoid the effect of inductance by using not too low a discharge resistance. For the shorter times this implies the use of a rather low capacity in order to get the required value of RC. The capacity used must not be so low that that of the circuit itself ceases to be negligible. Fortunately, the capacity of the circuit has proved to be rather small.

(*b*) *Capacity of circuit.* The discharge circuit has a capacity of its own, the value of which depends upon the way in which it is measured. Small condenser capacities are used in practice only for rapid discharges, and since the capacity of the circuit itself is always rather small, however measured, it is only with rapid discharges that it might become important. To make the circuit capacity negligible in comparison with the condenser capacity the latter should be kept as large as other considerations permit; since, however, for a given value of the discharge time RC, R must be at least 36 L/RC (see preceding section) there is a limit to the value of C allowable; and the possible trouble discussed in section (*d*) below is less if R is greater, *i.e.* C smaller.

The best way to determine the extra capacity C_1 and the extra inductance L_1, of the discharge circuit itself is, in Fig. 1, to connect K to (1) by turning the switch, and a to f by adjusting the commutator, and to replace the condenser C by an oscillating circuit consisting of a suitable capacity C_2 and inductance L_2. The total inductance of the circuit then is (L_1+L_2), the total capacity (C_1+C_2), and the period of oscillation $2\pi\sqrt{(L_1+L_2)(C_1+C_2)}$. A hot-wire thermocouple (vacuo-junction) in the circuit, with its couple connected to a galvanometer, allows resonance with a calibrated wavemeter to be determined. The oscillation frequency of L_2 with C_2 being P_0 and of (L_1+L_2) with (C_1+C_2) being P, we have

$$(1+L_1/L_2)(1+C_1/C_2)=P_0^2/P^2.$$

By making L_2 rather small and C_2 so large that C_1/C_2 is negligible, L_1/L_2 can be determined. By making L_2 large and C_2 small, C_1/C_2 can be determined. In this way L_1 and C_1 can be found with considerable accuracy. The following values were obtained with a Sullivan wavemeter and various frequencies between 400 and 1000 kilocycles per second:

Circuit A (neurothermic): inductance $8\,\mu$H, capacity 0.
Circuit B (Scott's): inductance $11\,\mu$H, capacity $2\,\mu\mu$F.

Thus for high-speed discharges, corresponding to high-frequency oscillations, the extra capacity of the circuit itself is negligible (see section (*d*) below). The large extra capacity found by other methods is due to absorption of electricity into the insulation, or similar causes; the energy of the discharge is not increased by it, nor can the stimulating efficacy be. The discharge of this extra capacity is too slow to affect the rapid shocks; and with slow shocks the condenser capacity has to be so large in any case that the extra capacity is negligible. Thus, with reasonable precautions, the capacity of the circuit itself can be neglected, provided that the condenser capacity be not reduced below about $500\,\mu\mu$F.

(*c*) *Leakage*. With a condenser of small capacity, if the insulation in lines or commutator were faulty, there might be appreciable loss of charge while the brush *a* passed across the intervening insulator from the charging to the discharging segment. With all the commutator rings employed, when brush *a* was resting on the insulator between two segments, the discharge of C (Fig. 1) went on at a rate corresponding to a resistance of about 2000 megohms (neurothermic circuit) or 4800 megohms (Scott's circuit). At a very low frequency (*e.g.* 4 shocks per sec.) the interval available for leakage between successive contacts on charge and discharge segments might be as great as 0·03 sec. (With the commutator of many segments the time might be greater, but this should not be used for very low frequencies.) Even with a capacity as low as $0{\cdot}001\,\mu$F the amount lost by leakage in 0·03 sec., in the two circuits, would be respectively 0·6 and 1·4 p.c. of the initial charge. Thus, with these commutators and circuits, loss by leakage of charge is of no importance except in very unusual circumstances which should be guarded against.

With the commutator ring of many segments (type (*c*)) the resistance between G and F is about 200 megohms. This allows a very small constant current to run in the circuit, which is without effect; it has no influence on the maintenance of its charge by the condenser.

(*d*) *Contact between brush and commutator.* With the shorter discharge times discharge will be complete before the brush running on the commutator has come any considerable distance into contact with the discharge segments. The circumference of the commutator rings is about 15 cm., and even at the highest speed, say 100 rev. per sec., the linear speed past the brush is only 1500 cm. per sec. In 1 microsecond the brush would come 1500×10^{-6} cm. $= 15\,\mu$. A considerable part, therefore, of the discharge might be complete before the contact of the brush with the commutator had exceeded 2 or $3\,\mu$. At lower speeds of the commutator the distance travelled by the ring under the brush, before the discharge was effectively completed, would be still less.

It seemed *a priori* very unlikely that the commutator would be so smooth and the brush so good that contact of this instantaneous character would be established without introducing at the first moment of contact a resistance sufficient to disturb the time relations of discharge. It would be possible to test this experimentally by putting the condenser discharges into a cathode-ray oscillograph and observing them directly. A simpler method, however, is available by the use of a vacuo-junction and a galvanometer as follows.

If there be a resistance at the contact between brush and segments then a corresponding proportion of the *energy* of discharge will be lost at the contact. Let us introduce into the discharge circuit the hot wire of a vacuo-junction, or an insulated resistance wire wound non-inductively on a thermopile, and connect thermo-element or thermopile to a galvanometer. The greater the resistance at the contact the less will be the energy received by the hot wire. Let us, with constant frequency, vary the capacity C and the voltage V and find the ratio of steady reading to CV^2. If this is the same for large capacities (slow discharges) as for small capacities (rapid discharges), there cannot be appreciable resistance at the contacts since these are bound to be more efficient with slow discharges. If there is a resistance at the contacts, the rapid discharges (small capacities) will give a smaller reading for a given CV^2.

An even more complete test is to find the value, in absolute energy units, of 1 mm. deflection of the galvanometer connected to vacuo-junction or thermopile, for the two cases (I) direct current (condenser short-circuited), and (II) condenser discharges. If these agree there cannot be appreciable loss of energy at the contacts on the commutator.

A number of tests of this kind were made of which the general result is as follows. There is no appreciable loss of energy at the contacts provided that in the discharge time RC the ring has travelled under the brush a distance of at least 0·01 mm. This seems to allow a sufficiently good contact to be made. For short discharge times, therefore, it is necessary to have a high linear speed of the commutator ring, which means, unless a very high frequency of stimulation is to be employed, that the ring must have comparatively few segments. For work such as that by Scott [1934] it is better to use a ring with a single pair of segments driven at a rather high speed.

Provided, therefore, that the surface speed of the commutator ring is high enough, and that suitable precautions are taken, the shocks run exactly to schedule right down to discharge times of a microsecond. This will not be the case if the commutator be allowed to become dirty or the brush out of shape, and for security in experiments with very short discharge times it is better to introduce a vacuo-junction, or a hot wire wound on a thermopile, into the discharge circuit, and at intervals to check the working with a galvanometer. A resistance has to be introduced in any case, and this could include the hot wire.

It is astonishing perhaps that such good results are obtained with so little trouble. The commutator ring must be treated with care and allowed a very small amount of good oil. The brush must be adjusted to make a good contact with it at an obtuse angle; it should be of thin copper or phosphor-bronze strip, suitably supported with a spring, with its end cut accurately parallel to the segments. With reasonable precautions and due attention to the factors discussed above, the arrangement is capable of great accuracy and it is very convenient in use.

Sparking at the contacts, due to a combination of a large capacity and a high voltage, must of course be absolutely avoided.

A further source of error, but of an elementary kind, would be due to driving the commutator at a speed too high to allow discharges to take place between successive contacts. For this reason the "rheobase" cannot be reached during repetitive stimulation at any but a very low frequency. Discharge being $e^{-t/RC}$, the charge has fallen to a negligible value when t/RC = say, 4. Thus the time of contact on a segment must not be less than $4RC$. This time, with the 46-segment commutator, is about 40 p.c. of the whole cycle (charge and discharge); thus the interval between discharges must not be less than about 10 RC. If, for example, we were using a discharge time of 1σ, $RC=10^{-3}$, the interval between successive shocks should not be less than 10σ; the frequency, therefore, must not be more than 100/sec. Thus high-frequency stimulation cannot be applied when the discharge time is long.

SUMMARY.

For repetitive stimulation of nerve or muscle, with electric shocks of known frequency, intensity and discharge time, a revolving commutator of adjustable speed, with variable condenser and potential, is convenient and accurate. With simple precautions the effects of (*a*) inductance, (*b*) capacity, (*c*) leakage, (*d*) imperfect contact between brush and commutator, and (*e*) incomplete discharge, can be avoided, and it is possible to work with frequencies as high as 2500 per sec. and with discharge times as short a 1 microsecond.

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