

## THE CONDITIONS OF RECOVERY OF TRANSMISSIVITY OF NEWLY REPASSIVATED IRON WIRES IN NITRIC ACID

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In strong nitric acid (*e.g.* 70 volumes per cent<sup>1</sup>) the activation reaction travels over the surface of the passive iron wire in the form of a clearly defined area or "wave" of limited length. In a typical circuit transmission in a pure iron wire (*e.g.*, Armco wire) suspended in HNO<sub>3</sub> of 78–80 v. per cent at 15° this wave has a length of 12 to 15 cm. and a speed of *ca.* 15 cm. per second.<sup>2</sup> The length (*L*) is determined by the relation between the speed of transmission (*S*) and the duration of the reaction (*T*) at each element of surface (*i.e.*,  $L = ST$ ), and decreases as the concentration of HNO<sub>3</sub> increases. At any point on the surface the metal reacts with the acid for a brief time (*ca.* 1 second in the instance cited) and instantly becomes passive again. The duration of the local reaction is thus given if we measure the speed and the length of the wave; this is most conveniently done in wires enclosed in glass tubes containing the acid,<sup>3</sup> using a millimeter rule and stop-watch. Two processes are thus concerned in the formation of the wave; the first is the local activating process of electrochemical reduction, which disrupts the passivating film and allows metal and acid to interact; the second is the oxidative reaction which restores the film and repassivates the wire. Transmission depends on the first; the second may be compared with the recovery process in the irritable living element; *i.e.*, it is similar in its general relations to the process occurring during the earlier part of the refractory period, by which the just activated nerve fibre or muscle cell regains its tempo-

<sup>1</sup> 70 volumes of HNO<sub>3</sub>, C.P., sp. gr. 1.42, in 100 volumes of solution.

<sup>2</sup> Lillie, R. S., *Science*, 1929, **69**, 305.

<sup>3</sup> Lillie, R. S., *J. Gen. Physiol.*, 1924–25, **7**, 477.

rarily lost reactivity. In strong acid (> 55 v. per cent) the wire always shows this prompt spontaneous repassivation.

Whatever may be the conditions in nerve or muscle, we know that in the iron wire the recovery process consists in the production of a new surface film having the same properties as the original film before activation. Repassivation, however, constitutes only one part of the whole recovery process. In general, two distinct phases may be distinguished in this process: first, the formation of the adherent and impermeable oxide film which confers passivity: this occurs rapidly, its most definite index being the electromotor variation of passivation;<sup>4</sup> second, the more prolonged phase during which the repassivated wire, which at first transmits imperfectly, regains by degrees its original transmissivity. Schematically we may represent the sequence of events thus:

*Recovery Process*

- (1) Phase of repassivation
- (2) Phase of imperfect transmission
  - (a) period of decremental transmission
  - (b) period of complete but relatively slow transmission

When we activate a series of similar passive wires in 70 v. per cent HNO<sub>3</sub> at regularly increasing intervals after a previous activation the phenomena of transmission are observed to vary with time in the following manner. At first the transmission is typically decremental; *i.e.*, the activation wave travels for only a limited distance and then stops short. As time advances the distance travelled increases, and eventually transmission becomes again complete, although at first it is slower than in a completely recovered wire; by degrees it regains its original speed.<sup>5</sup> A similar variation in transmissive properties has been shown to occur in muscle and nerve during the refractory period.<sup>6</sup>

<sup>4</sup> Cf. the string galvanometer curves in Fig. 8 of my recent paper in *J. Gen. Physiol.*, 1929-30, 13, 1.

<sup>5</sup> Lillie, R. S., *J. Gen. Physiol.*, 1920-21, 3, 107.

<sup>6</sup> *I.e.*, the speed of transmission increases progressively during the relative refractory period. For muscle (cardiac) cf. Mines, G. R., *J. Physiol.*, 1913, 46, 349; Ashman R., *Am. J. Physiol.*, 1925, 74, 121; for nerve cf. Forbes, A., Ray, L. H., and Griffith, F. R., Jr., *Am. J. Physiol.*, 1923, 66, 553; Gasser, H. S., and

The duration of the entire recovery period varies with the nature of the wire, the concentration of  $\text{HNO}_3$ , the presence of foreign (*e.g.* surface-active<sup>7</sup>) substances, and the temperature.<sup>8</sup> In pure soft iron wire in 70 v. per cent  $\text{HNO}_3$  at 20° it lasts for only a few seconds,<sup>9</sup> while in steel (piano) wire it lasts 15 minutes or more.<sup>3</sup> The precise reason for this difference of behavior in different kinds of wire is unknown, but is apparently related to the special structure of the metallic surface.

The present observations were made with steel wires and have reference to the minimal time required for the wire, activated in strong acid and immediately immersed in a known solution of  $\text{HNO}_3$ , to recover its ability to transmit completely or non-decrementally *in strong acid*. In these experiments recovery (apart from the automatic repassivation) thus proceeds in a different concentration of acid (in most cases) from that in which the wire was originally activated. What is determined is the relation between the concentration of the acid surrounding the wire during the second part of the recovery period and the rate at which it reaches a certain definite stage of recovery, as shown by its ability to transmit completely when transferred to strong acid and then immediately activated.

It should be noted that in each experiment the wire is exposed successively to three separate baths of nitric acid: these are (1) the bath (usually of 70 v. per cent  $\text{HNO}_3$ ) in which it is first activated (called Bath A); (2) the bath of varying concentration to which it is

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Erlanger, J., *Am. J. Physiol.*, 1925, **73**, 613. In compressed cardiac muscle the early stage of block (which later gives way to complete but slow transmission) corresponds to the decremental stage. It is uncertain at present whether a decremental stage exists during the so-called absolute refractory period of nerve.

<sup>7</sup> The period of repassivation is prolonged several times in 70 v. per cent  $\text{HNO}_3$  to which a small quantity of a surface-action compound, *e.g.*, 0.5 per cent amyl alcohol (soon oxidized to caproic acid), is added. This is an effect of interference with the surface reaction. Correspondingly transmission is greatly slowed in such a mixture.

<sup>8</sup> For the temperature influence *cf.* Lillie, R. S., *J. Gen. Physiol.*, 1924-25, **7**, 477.

<sup>9</sup> Complete transmission returns within a second or less in Armco wire under these conditions,<sup>2</sup> but several seconds more are required before the original speed is regained.

then immediately transferred and in which it lies undisturbed for the measured time allowed for recovery (Bath B); and (3) the bath containing strong  $\text{HNO}_3$  (70 v. per cent or 100 v. per cent in these experiments) to which it is transferred after the lapse of the period of recovery; in this bath (Bath C) it is immediately activated by touching at one end with zinc; the distance travelled by the activation wave is then measured. The transfers are made with platinum-tipped steel forceps.

The wire used was steel wire<sup>10</sup> of the same kind as in my former experiments on transmission and recovery.<sup>3</sup> The lengths of wire, 50 cm. each, were partly dissolved in nitric acid to remove the surface layer of metal, a procedure favorable to uniformity of behavior.<sup>3</sup> In each experiment several completely recovered passive wires were first placed side by side in a porcelain trough containing 70 v. per cent  $\text{HNO}_3$  (Bath A). They were then activated simultaneously (within 2 or 3 seconds) and immediately transferred to a second trough (Bath B) containing the acid whose influence on recovery was to be tested. After definite periods of time in this acid the wires were transferred singly to the strong acid (70 v. per cent or pure 1.42  $\text{HNO}_3$ ) in which the test for transmissivity was made (Bath C) and immediately activated. From previous experiments the probable limits of the recovery times were already known, and the exposures of the several wires in each experiment were timed so as to include a series of partial recoveries (shown by decremental transmission) in addition to the complete recovery. The intervals between the successive transfers varied (according to the strength of acid used in the different experiments) between  $\frac{1}{4}$  minute and 2 minutes. This interval in any single determination represents the approximation to the true recovery time.

Protocols of a number of experiments are given in Table I to illustrate the kind and degree of the variations observed in different solutions of acid.

It will be noted that complete recovery during immersion in 30 v. per cent  $\text{HNO}_3$  required 22 minutes in one case, 23 minutes in another; in 50 v. per cent  $\text{HNO}_3$  the wires in all three experiments were com-

<sup>10</sup> No. 20 piano wire (music steel wire) from the Spencer Co., Worcester, Massachusetts.

pletely recovered after 17 minutes, 16 minutes being nearly sufficient in one case; in 80 v. per cent  $\text{HNO}_3$  an exposure of  $11\frac{1}{2}$  minutes was sufficient in two cases and nearly so in the third.

Before considering the general results of these measurements, certain peculiarities in the behavior of wires activated while immersed in weak acid should be described. The description of the recovery process on page 350 has had reference to wires activated in strong acid and allowed to recover in the same acid. If passive wires are activated in weak acid (of 50 v. per cent or less) the phenomena are quite different. A wire activated in strong acid, immediately transferred to weak acid, and there reactivated by touching with zinc, instantly

TABLE I

Distances travelled<sup>11</sup> by activation waves in wires activated in pure 1.42  $\text{HNO}_3$  after having been exposed to  $\text{HNO}_3$  of varying concentrations at  $20^\circ$  for varying periods of time after a previous activation in 70 v. per cent  $\text{HNO}_3$ .

A. 30 v. per cent $\text{HNO}_3$			B. 50 v. per cent $\text{HNO}_3$				C. 80 v. per cent $\text{HNO}_3$			
Exposure	Distances (cm.)		Exposure	Distances (cm.)			Exposure	Distances (cm.)		
	Exp. 1	Exp. 2		Exp. 1	Exp. 2	Exp. 3		Exp. 1	Exp. 2	Exp. 3
<i>minutes</i>			<i>minutes</i>				<i>minutes</i>			
16	8.3	10.0	12	10.1	9.1	8.4	9	14.8	13.3	13.0
20	27.5	21.8	14	11.2	13.2	18.4	10	23.2	21.1	15.8
22	34.2	Full	16	22.7	26.3	42.0	11	28.1	30.3	18.0
23	Full		17	Full	Full	Full	$11\frac{1}{2}$	Full	Full	38.3

transmits rapidly along its whole length and *remains* active, *i.e.*, effervescence and solution continue unchecked until the whole wire is dissolved. In this case the decremental stage is entirely absent,

<sup>11</sup> In my earlier paper of 1920,<sup>5</sup> transmission for a distance of 20 cm. was regarded as evidence of full recovery. I have since found, by the use of longer troughs, that transmission waves, especially in stronger acid (*e.g.* 1.42  $\text{HNO}_3$ ) will at times (although infrequently) come to a stop after travelling for 30 or 35 or even (in a few cases) 40 cm. along the wire. Transmission for 50 cm. may safely be regarded as complete. It should be remembered, however, that accidental irregularities in the composition of the metallic surface may at times interfere with transmission in wires otherwise completely recovered.

as is also the spontaneous repassivation or recovery.<sup>12</sup> Such an experiment is instructive in several respects; it shows (what was already known<sup>13</sup>) that automatic repassivation requires a certain minimal concentration of  $\text{HNO}_3$ ; it also shows that the condition which determines repassivation is the same as the condition which renders the wire for a time decrementally instead of completely transmissive. This condition may be defined as more than a certain critical intensity of oxidative action.

It is evident that decremental transmission depends on some special peculiarities of the newly formed passivating film, since it disappears if the passive wire remains for a certain time in the acid. The nature of the conditions may perhaps best be indicated as follows. If we take a wire at a certain stage of recovery in 70 per cent  $\text{HNO}_3$ , *e.g.* one minute after activation in this solution at  $20^\circ$ , we find that it transmits completely if transferred to 50 per cent  $\text{HNO}_3$  and then activated; but only for 1 or 2 cm. if activated in 70 per cent acid, and hardly at all in 100 per cent (1.42) acid. In general, at a given interval after a previous activation the distance of transmission is less (*i.e.*, the degree of decrement is greater) the stronger the acid in which the wire is activated.<sup>13</sup> At the region occupied by the activation wave each element of surface is the seat of two distinct chemical processes which are opposed in their general effect, the one being reducing (film-disruptive), the other oxidative (film-forming). The relative intensities of these two processes determine which one gains the upper hand. If the oxidative process has more than a certain intensity, the surface film of oxide rapidly becomes continuous and impermeable to acid, and the reaction ceases; if it has less than this intensity, no effective or stable film is formed and the reaction continues unchecked.

<sup>12</sup> This does not mean that a newly repassivated wire left undisturbed in weak acid shows no phenomena of recovery; such a wire, in fact, shows the same kind of change as a wire in strong acid during the period succeeding the decremental phase; *i.e.*, the speed with which it transmits is relatively slow at first and becomes more and more rapid as time elapses up to a maximum. This can most readily be shown by timing with a stop-watch the speeds of transmission of a series of passive wires in glass tubes containing the weak acid, at varying intervals after the previous activation in strong acid.

<sup>13</sup> *Cf.* my early paper on recovery in steel wires, *J. Gen. Physiol.*, 1920-21, 3, 107.

In the case of the typical automatically reversed activation reaction in strong acid it is clear that the surface oxidation which reforms the film also imparts to it at the same time some structural or other character which at first is unfavorable to transmission, as shown by the decremental phase of early recovery. The succeeding change from decremental to non-decremental transmission is the index of some progressive chemical or structural change occurring in the passivating film under the influence of the surrounding acid. Experiments with different concentrations of  $\text{HNO}_3$  show that the rate of this change is a direct function of the concentration. To illustrate: in a series of preliminary observations the wires were activated in 70 v. per cent  $\text{HNO}_3$  and were allowed to recover in acid of the four concentrations given in Table II. The exposures required to render them again completely transmissive in 70 v. per cent  $\text{HNO}_3$  were as follows:

TABLE II

Concentration (v. per cent $\text{HNO}_3$ of 1.42 sp. g.)	Minimal exposures for restoration of non-decremental transmission in 70 v. per cent $\text{HNO}_3$ (minutes at 19°-20°)
10	<i>ca.</i> 25
25	> 11 (est. <i>ca.</i> 14)
70	6-7
100	3½-4

The rate of recovery is thus about seven times as rapid in the concentrated as in the 10 v. per cent  $\text{HNO}_3$ .

In a more complete series of experiments the exposures required to render the newly activated wires completely transmissive in 100 v. per cent (sp. gr. 1.42)  $\text{HNO}_3$  were determined for a series of concentrations between 15 v. per cent and 100 v. per cent. In general these exposures (for any given concentration) are about twice as long as those required to render the wires transmissive in 70 per cent  $\text{HNO}_3$ . This shows again that at a certain stage of recovery the passivating film has properties permitting complete transmission in the weaker but not in the stronger acid. The decremental transmission observed in the stronger acid at a time when the wire transmits freely in 70 per cent acid, is the expression of its more intense oxidative action; this interferes with the local reduction on which transmission depends.

The results of this series are summarized in Table III which gives the average minimal exposures required to render the wires non-decrementally transmissive in 1.42 HNO<sub>3</sub> at 19–20°. The number of separate experiments under uniform conditions (of the kind illustrated in Table I) made with each concentration of HNO<sub>3</sub> in Bath B is stated in brackets in the first column; the second column gives the averages and probable errors of these averages;<sup>14</sup> in the third column are the products of the concentrations into the effective times of exposure.

The results of the two series are represented graphically, with both linear and logarithmic coordinates, in Fig. 1. The former curves are

TABLE III

Concentration (C) (v. per cent HNO <sub>3</sub> of sp. gr. 1.42) (number of separate determinations in brackets)	Minimal exposures (T) for restoration of non-decremental transmission in 100 v. per cent HNO <sub>3</sub> (minutes at 19°–20°)	CT
15 (4)	<i>ca.</i> 40	<i>ca.</i> 600
20 (36)	35.5 ± 0.47	710
30 (18)	23.4 ± 0.26	705
40 (7)	19.6 ± 0.17	784
50 (12)	16.6 ± 0.10	830
60 (14)	14.1 ± 0.11	846
70 (23)	12.4 ± 0.15	868
80 (8)	11.4 ± 0.11	912
100 (16)	10.5 ± 0.13	1050

hyperbola-like in their general character, although departing considerably from the rectangularity which would correspond to a direct proportionality between concentration and rate of recovery. This proportionality is approached in the lower concentrations; but above 50 v. per cent the recovery becomes progressively slower, in relation to concentration, as the latter increases. In the curves with logarithmic coordinates the points of both series fall approximately on straight lines, indicating that the film is altered during recovery at a rate closely proportional to the external concentration of acid.

Apparently the passivating film, at its first deposition in the strong

<sup>14</sup> Calculated by Peters' approximation formula (*cf.* Mellor, J. W., Higher mathematics, Longmans Green and Company, London, 1926, 524).



acid, has some structural or other character, such as thickness, irregular orientation of molecules, or possibly a less intimate contact with the metallic surface, which makes it relatively resistant to electrolytic reduction. Whatever the precise conditions may be, it is clear that under the action of the external acid this character changes in such a manner as to render the film progressively more reducible. The final

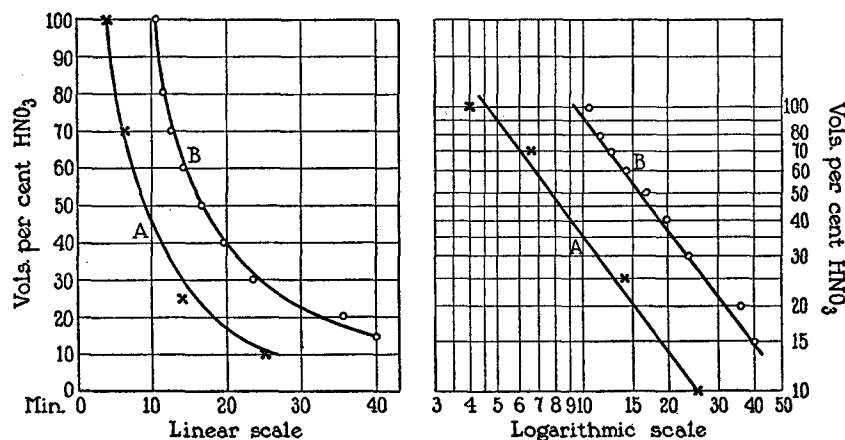


FIG. 1. Times of immersion in HNO<sub>3</sub> of different concentrations required for recovery of complete or non-decremental transmissivity. A, for transmission in 70 v. per cent HNO<sub>3</sub>; B, for transmission in pure (100 v. per cent) HNO<sub>3</sub> (of s.g. 1.42). Temperature 19–20°. Ordinates, vols. per cent HNO<sub>3</sub>; abscissae, minutes. Data are plotted with both Cartesian and logarithmic coordinates.

or limiting state, corresponding to maximal speed of transmission (or stage of complete recovery), is the stage at which the film is most readily reduced. This is shown further by the fact that the threshold of electrical activation of the wires is then lowest.<sup>15</sup>

<sup>15</sup> This can best be shown by determining with the Lucas pendulum the duration of the constant current, of known E.M.F., required to activate the passive wire electrically. I have made numerous experiments of this kind with pure iron wires (Armco) during the past few years; in general under similar conditions of recovery in 70 v. per cent HNO<sub>3</sub> the product  $i\sqrt{t}$  ( $i$  being the intensity and  $t$  the minimal or threshold duration of the activating current) remains nearly constant throughout a wide range of intensities (between 1 and 8 volts). This product is highest shortly after repassivation and decreases progressively as time elapses to a minimum corresponding to complete recovery. A correlation between electrical

The hypothesis of a solvent action by which the outer layers of the oxide sheet (assumed at its first deposition to be several molecules thick) are dissolved away as ferric nitrate seems the best adapted to explain the general course of the recovery process. The same final stage is reached in the different solutions of  $\text{HNO}_3$ , but at a rate which varies with concentration in the manner described. The relation between concentration and rate of recovery is not far from proportional in the weaker solutions up to 50 v. per cent,—*i.e.*, there is an approach to a mass action relationship; but in the stronger solutions the rate of recovery becomes somewhat slower, relatively to concentration, as the latter increases. This may indicate the superposition of two actions, one the direct solvent action of the acid on the film, the other some further oxidative action (possibly intermittent) upon the metal, having the effect of renewing or reinforcing the film wherever it becomes defective and so retarding its dissolution. This apparent interference is well marked in the passivating concentrations ( $> 55$  v. per cent) and becomes more distinct as the concentration increases. Occasionally, under conditions difficult to define, I have found wires to remain decrementally transmissive for abnormally long periods, even several hours, while immersed in pure 1.42  $\text{HNO}_3$ . This refractory behavior is certainly an effect of strong oxidation. On the general view just indicated the state of decremental or slow transmissivity would correspond to the presence of a relatively thick oxide sheet; while maximal speed would indicate minimal thickness, possibly monomolecular. Further thinning in the strong acid would be automatically prevented, because any accidental local interruptions exposing the metal, being local anodes with high current density, would instantly be repaired.<sup>16</sup>

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sensitivity and speed of transmission is thus present in the passive iron system as well as in the irritable living system such as nerve. (For this correlation in nerve *cf.* Erlanger, J., and Gasser, H. S., *Am. J. Physiol.*, 1924, **70**, 624; 1930, **92**, 43.)

<sup>16</sup> This is a feature of the behavior in strong acid (for a brief discussion of the general conditions *cf.* my paper in *J. Gen. Physiol.*, 1929–20, **13**, 1, footnote p. 7). In weak acid such automatic tendency to repair is slight or absent. In fact one practical difficulty in determining the duration of the recovery periods in long passive wires in weak acid is that such wires are likely to become suddenly active, at irregular and unpredictable intervals, without any apparent inciting cause;

With regard to the bearing of these observations on the problem of the conditions of recovery in irritable living tissues such as nerve, only a few general remarks need be made. According to the membrane conception of the primary stimulation process, the fundamental similarity between the iron wire model and the living tissue is that in both systems the material whose chemical reaction furnishes the condition of transmission forms part of a thin, highly impermeable film which is situated at the boundary between two chemically dissimilar phases. The impermeability (or semi-permeability) depends on the special chemical and structural composition of the film; it also furnishes the condition for the characteristic electrical P.D. between the phases. Hence any sufficient local alteration in the film causes a variation of potential and gives rise to local currents between the altered and the unaltered regions. It is because of this special situation of the reactive material in the electrically polarized film that the latter is subject to chemical and structural change under the influence of electric currents passing between the phases; transmission depends directly upon this condition, local circuits, with associated distance-action effects, arising wherever the film is broken down or sufficiently altered.

Accordingly we regard the primary phase of recovery in the irritable living system as consisting in the replacement of some material

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especially in acid of 10 to 20 v. per cent is this spontaneous activation so frequent that many experiments have failed from this cause alone. Evidently the indefinite preservation of passivity depends on local automatic repassivation, *i.e.*, is an active rather than a merely passive phenomenon, resembling in this respect the preservation of semi-permeability in the membranes of living cells. It is interesting to note that Bishop (Bishop, G. H., *J. Gen. Physiol.*, 1927-28, 11, 159) observed an irregular oscillating or flickering effect, the indication of minute local currents, when the passive wire was connected to the cathode ray oscillograph through an amplifier. The instability of the passive state in weak acid is thus readily understood. Correspondingly the threshold of electrical activation is low in such solutions, and in general decreases rapidly with the concentration of acid. In highly dilute acid passive wires are activated with extreme ease, mechanically or otherwise. It would seem that in wires lying undisturbed in such acid any minute local area where the film becomes discontinuous is not repaired but instantly spreads. The time and locus of such an occurrence are apparently a matter of chance, hence short wires will (as a rule) remain passive for much longer periods than long wires.

which is chemically broken down in the reaction of activation; this material is essential to the normal semi-permeability and electrical polarization of the plasma membrane. But in addition to this replacement some further change, partly chemical, partly structural, seems to be required in both the living and the non-living systems. This change occupies the relative refractory period; its nature in the iron wire is partly indicated by the foregoing experiments, but with regard to the living system only conjecture is possible at present. There is much evidence that the characteristic semi-permeability of the living plasma membranes is dependent on their lipid components; but we have as yet no clear evidence that lipoids are altered during transmission, although in the case of nerve the production of ammonia<sup>17</sup> and the negative fact of an absence of increase in carbohydrate metabolism<sup>18</sup> may seem to point in this direction. Comparative metabolic studies on a variety of irritable tissues offer the best prospect of throwing light on this problem. The key to the situation is the constitution of the plasma membrane of the irritable element. Provisionally we may conceive of this membrane as a mosaic-like structure in which the channels permitting diffusion of ions are blocked during rest by the reactive material in question—possibly lipoid. This material, broken down during stimulation, is restored and rearranged during the recovery period.

#### SUMMARY

1. Passive steel wires were activated in a bath (Bath A) containing 70 v. per cent HNO<sub>3</sub> (in which they undergo prompt repassivation), and immediately transferred to a second bath (Bath B) containing HNO<sub>3</sub> of a concentration varying in different experiments. After varying intervals in this bath they were transferred while still passive

<sup>17</sup> Tashiro, S., *Am. J. Physiol.*, 1922, 60, 519; Gerard, R. W., and Meyerhof, O., *Biochem. Z.*, 1927, 191, 142.

<sup>18</sup> Gerard and Meyerhof found no change in lactic acid production during the stimulation of nerve (Gerard, R. W., and Meyerhof, O., *Biochem. Z.*, 1927, 191, 125). In a recent paper (*Am. J. Physiol.*, 1930, 93, 342) Holmes, Gerard, and Solomon have described experiments showing that stimulated nerve consumes no more carbohydrate than resting nerve. There is also evidence of increase in the soluble phosphate of nerve during activity, a fact again favoring the view that lipoids are concerned in transmission (*cf.* Gerard, R. W., and Wallen, J., *Am. J. Physiol.*, 1929, 89, 108).

to a third bath (Bath C) containing strong  $\text{HNO}_3$  (70 or 100 v. per cent) and there immediately activated.

2. During the immersion in Bath B the wires progressively recover their ability to transmit activation waves in strong  $\text{HNO}_3$ . The measure of this recovery is the distance travelled by the activation waves in Bath C after the varying times of exposure in Bath B. Transmissivity as thus measured is at first incomplete (decremental) and later becomes complete. The minimal exposures in Bath B required to render wires completely transmissive in the strong acid of Bath C were determined for concentrations of  $\text{HNO}_3$  between 10 and 100 v. per cent. With 100 v. per cent  $\text{HNO}_3$  in Bath C, these exposures range from 40 minutes or more in 15 v. per cent to 10 minutes in 100 v. per cent  $\text{HNO}_3$  (temperature 19–20° in all baths).

3. The time required for complete recovery varies inversely with the concentration of the acid in the recovery bath (Bath B), but increases rapidly with the concentration of the acid in the testing bath (Bath C). Hence at a time when a wire has recovered just sufficiently to transmit non-decrementally in a given strong acid (*e.g.*, 70 v. per cent) it still transmits decrementally in a stronger acid. Complete recovery for transmission in 100 v. per cent  $\text{HNO}_3$  requires about twice as long as for 70 v. per cent  $\text{HNO}_3$ . In  $\text{HNO}_3$  of 50 v. per cent and less decremental transmission does not occur.

4. The indications are that recovery is an effect of the progressive solvent action of the external acid on the passivating oxide film, which at its first deposition appears to be relatively thick and hence resistant to electrochemical reduction. The final stage of recovery, when electrical sensitivity and speed of transmission are maximal, would on this hypothesis correspond to minimal thickness, possibly monomolecular.

5. The rate of recovery in Bath B is not far from proportional to the concentration of  $\text{HNO}_3$  in the more dilute solutions, but in the higher, especially the strongly passivating, concentrations (70 to 100 v. per cent) the rate becomes appreciably slower than proportional, apparently because of the intense oxidizing action of these solutions, which reinforces the oxide sheet and retards the thinning process.

6. The bearing of these observations on the problem of the conditions of recovery in irritable living tissues (such as nerve) during the absolute and relative refractory periods is briefly discussed.