

## THE SENSORY THRESHOLD FOR FARADIC STIMULATION IN MAN<sup>1</sup>

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A method of measuring induction shocks which has recently been developed by one of us<sup>2</sup> offers the advantage of enabling the investigator to take into account all the sources of variation which are present in induced currents as applied to tissues, including the electrical resistance of the tissues studied, and the manner of contact of the stimulating electrodes—factors not hitherto measurable.

This method we have employed in determining the human sensory threshold for induction shocks. Our results are interesting, both as affording a basis of comparison between the human sensory threshold and the threshold for various activities in the lower animals, and for their own sake, as criteria of the condition of the receptive mechanism of the human body. Earlier studies of the electro-cutaneous sensibility of the human body are those of Munk and Leyden,<sup>3</sup> Bernhardt,<sup>4</sup> and Tschiriew and de Watteville.<sup>5</sup> Their results, however, have little significance, in view of the relatively large sources of error inherent in their methods.

*Method of Measuring Stimuli.*—This method consists, in essence, of determinations of the strengths of faradic stimuli in terms of primary current intensity and secondary coil position, with corrections for the resistance of the secondary circuit and for the precise mode of contact of the stimulating electrodes with the tissue. The expression for stimulation strength uncorrected for these last two factors is  $Z = (M/L) \times I$ ,  $Z$  being the stimulation strength,  $M/L$  the "calibration

<sup>1</sup> From the Laboratory of Physiology in the Harvard Medical School.

<sup>2</sup> Martin, 'The Measurement of Induction Shocks.' New York, 1912; also the *American Journal of Physiology*, Vols. XXII., 1908, and XXVII., 1910.

<sup>3</sup> Munk and Leyden, *Virchow's Archiv*, 1864, XXXI., p. 1.

<sup>4</sup> Bernhardt, 'Die Sensibilitätsverhältnisse der Haut, Berlin, 1814.

<sup>5</sup> Tschiriew and de Watteville, *Brain*, 1897, II., p. 163.

number" for the particular secondary position used, and  $I$  the primary current in amperes. To correct for secondary resistance and for electrode variation the expression  $\beta = AZ/(R+A)$  is employed. The value  $\beta$  represents the effectiveness of the stimulus at the actual seat of stimulation, the physiological kathode or kathodes. Its validity rests upon the assumption that the resistance of these kathodes is negligibly small, since  $\beta$  signifies in actuality the amount of stimulus that would have to be used to obtain the observed result were the secondary resistance reduced to zero. For determining  $\beta$  a constant  $A$  must be established. This constant represents the influence upon the effectiveness of the stimulus of the mode of contact of the stimulating electrodes. To establish it two values,  $Z_R$  and  $Z_{R'}$ , must be determined for two secondary resistances,  $R$  and  $R'$ . The expression for  $A$  is  $(Z_R R' - Z_{R'} R)/(Z_{R'} - Z_R)$ .

*Stimulating Electrodes.*—At the outset of our investigation we were confronted with the problem of selecting and applying suitable stimulating electrodes. The first desideratum for satisfactory electrodes is that they shall minimize skin resistance. The horny layer of the skin with its oily secretions offers a relatively enormous resistance. We have obtained from a pair of platinum wire electrodes, pressed firmly against the finger tip, resistances ranging from 50,000 to 180,000 ohms. Obviously with such high initial resistances the opportunities for error are too manifold to permit one to have confidence in his results. A second essential feature of proper electrodes is that they shall maintain a perfectly uniform contact throughout the period of a single experiment. A third desirable feature is that the electrodes shall be as small as possible.

After experimenting with various sorts of electrodes we finally selected three types as meeting sufficiently one or all of the desiderata enumerated above to be worth using. Of these three one was to be applied to the lip and two to the fingers. The lip electrodes consisted simply of a pair of platinum wires bent over a small glass tube. By means of a harness fitting the head this glass tube was held so as to bring the platinum wires in firm contact with the mucous surface of the upper lip. These electrodes had the advantage of small stimulating

surface and also of maintaining a reasonably uniform contact between electrodes and tissues. Disadvantages presented by them were an undesirably high resistance, averaging above 30,000 ohms, and a possibility of being short circuited by the moisture of the lip.

Of the two types of finger electrodes one consisted of a pair of exceedingly fine steel needles soldered to flexible conductors and thrust horizontally about 2 mm. apart through the skin of the dorsal surface of a terminal phalanx. These electrodes satisfied the requirements of low resistance, small surface, and uniformity of contact. The only drawback to their use was a slight constant sensation of pain which sometimes became intense enough to interfere with accurate recognition of liminal shocks. The second type of finger electrodes consisted of a pair of small glass cylinders closed at their lower ends by corks through which platinum wires were inserted so as to extend a few millimeters into the cylinders. A drop of mercury covered each platinum wire, and the cylinders were filled above the mercury to within three centimeters of the top with strong sodium chloride solution. These electrodes were applied by flexing two fingers at the first joint and dipping their tips one into each cylinder to the depth of about two centimeters. Experiment showed that relatively considerable variations in the amount of immersion made no marked differences in the sensitiveness of the regions immersed. These electrodes proved the most satisfactory of those we used in respect to securing low resistance and strict uniformity of contact. Their large size introduced the objection that a great many receptors and much non-sensitive tissue were in the path of the shocks. The effect of this situation in actual practice will be discussed in later paragraphs.

*Method of Experimentation.*—In order that the subject of the experiment might not be distracted by the experimental procedures, wires were carried from the secondary coil of the calibrated inductorium through the wall into an adjoining room, where they terminated in connection with a pair of stimulating electrodes. A telegraph system connecting the two rooms enabled the subject and the experimenter to com-

municate with each other at pleasure. To avoid errors resulting from a possible diurnal variation in threshold each subject was experimented upon as nearly as possible at the same hour each day. The subject seated himself comfortably before a table on which rested a telegraph key and sounder, and adjusted the stimulating electrodes to lip or fingers as required. The experimenter, sitting before the stimulating apparatus in the next room, upon receiving notice that the subject was ready, began sending "break" shocks of calculable intensity at irregular intervals ranging from one to five seconds. The subject indicated by a telegraph signal whenever he felt a shock. The threshold was thus quickly determined, and by repeated tests shown to be the true one for the conditions then obtaining; next additional non-inductive resistances of twenty thousand, forty thousand and sixty thousand ohms, or in some experiments of forty thousand, seventy thousand and one hundred thousand ohms were successively introduced into the secondary circuit, and the threshold for each resistance determined in similar fashion. Readings for three additional resistances were taken instead of for just one, as required by the theory, in order to insure that serious errors should not creep in undiscovered. By thus obtaining four distinct thresholds at different resistances the calculation of four  $\beta$ 's for the same stimulus becomes possible, and a serious discrepancy among these  $\beta$ 's indicates at once that experimental errors have entered. Our practice has been to reject as untrustworthy any experiment in which three of the four calculated  $\beta$ 's failed to agree within ten per cent.

After the series of thresholds had been obtained, the secondary circuit, including the tissue being stimulated, but not the secondary coil, was connected with a Wheatstone bridge and its resistance determined by the Kohlrausch method. This resistance plus that of the secondary coil, which was known, and therefore not determined each time, gives the secondary resistance as a whole, and in connection with the data previously obtained permits the calculation of the specific sensory threshold for the particular conditions obtaining at the moment of the experiment. The whole

procedure was usually completed in about ten minutes. To illustrate the method of making the calculations the protocol of a single experiment is given below:

January 8, 1912. Subject M., experimenter P. Stimuli applied by means of wire electrodes on upper lip.

Secondary Resistance	Tissue Only —R— 23,000 Ohms	—R'— 63,000 Ohms	—R''— 93,000 Ohms	—R'''— 123,000 Ohms
Position of secondary coil...	17.7 cm.	14.7 cm.	13.8 cm.	13.2 cm.
Value of $\frac{M}{L}$ .....	381	986	1,400	1,790
Primary current in amperes —I—.....	0.5	0.5	0.5	0.5
Above corrected for core magnetization <sup>1</sup> .....	0.555	0.555	0.555	0.555
$Z = \frac{M}{L} \times I$ .....	211 = $Z_R$	548 = $Z_{R'}$	777 = $Z_{R''}$	994 = $Z_{R'''}$
A, from formula $A = \frac{Z_R R' - Z_{R'} R}{Z_{R'} - Z_R}$ .....		2,080	3,100	3,960
Average A.....	3,000			
$\beta = \frac{AZ}{R + A}$ .....	24.3	24.9	24.3	23.7
Average $\beta$ = .....	24.4			

*Validity of  $\beta$  as a Measure of the Sensory Threshold.*—If the value  $\beta$ , as determined by the method just described, is a true measure of the sensory threshold, we should be able to obtain closely concordant values of  $\beta$  in repeated experiments provided the sensory threshold of the subject has not varied meanwhile and notwithstanding variations in tissue resistance or in the method of applying the stimulating electrodes. As a test of the validity of our use of  $\beta$  in the manner indicated, we made five sets of experiments in duplicate on three different subjects, using the three types of electrodes described above. The interval between the first and second experiments of one set ranged from less than one half hour to more than two and one half hours; the five sets of experiments were carried out on five different days. These experiments, in our belief, demonstrate clearly the validity of the method adopted for measuring the sensory threshold, for in every one of them there was a close agreement between the two determinations

<sup>1</sup> For method of correcting for core magnetization see Martin, 'The Measurement of Induction Shocks,' p. 46.

of  $\beta$  although the resistance and the value of the constant  $A$  varied widely. The greatest difference in the values of  $\beta$  noted in any experiments amounted to 6.5 per cent. The average difference in all five was 3.5 per cent. The protocol of a representative one of these experiments is as follows:

February 16, 1912. Subject N., experimenter M. Stimulus applied to fingers through liquid electrodes.

1st observations: 2:30 P. M.  $Z$ , tissue only, 193; tissue resistance, 5,800 ohms; calculated  $A$ , 8,400;  $\beta$ , 104.

2d observations: 3:30 P. M.  $Z$ , tissue only, 265; tissue resistance, 8,300 ohms; calculated  $A$ , 5,800;  $\beta$ , 100.

As illustrating the superiority for measuring induction shocks, of  $\beta$ , in which secondary resistance is taken into account, over  $Z$ , in which secondary resistance is not considered, it is interesting to compare the values of  $Z$  given in these same five sets of experiments. The greatest difference between one  $Z$  and the other of a pair amounted to 27.2 per cent. The average in all five experiments was 15.3 per cent., differences more than four times as great as those noted above for the compared values of  $\beta$ .

*Comparison of the Human Sensory Threshold with the Threshold for Various Activities in Other Animals.*—When induction shocks are used as stimuli in ordinary animal experimentation, the stimulating electrodes can usually be placed advantageously with reference to the region to be studied. If the tissue stimulated is nerve the electrodes are in immediate contact with it, and carefully shielded to avoid escape of current to surrounding tissues. When muscle is stimulated directly the electrodes are so placed as to confine the current to the stimulated tissue. In experiments upon human subjects, on the other hand, the stimulating electrodes cannot be placed so advantageously. More or less escape of current is inevitable, and we cannot hope therefore to obtain human thresholds strictly comparable with those yielded in studies of lower animals.

The nearest approach in our experiments to the conditions obtaining in work upon experimental animals seemed to be in connection with the use of needle electrodes thrust through the skin. We had here, presumably, fairly intimate contact

of the electrodes with the receptors whose sensitiveness was under investigation. The electrodes were so near together as to make it probable that the greater part of the stimulating current passed directly from one to the other, with little escape to other tissues. Under these conditions we obtained values of  $\beta$  as follows:

Subject N. Average  $\beta$  (7 experiments) 14; subject P. Average  $\beta$  (3 experiments) 18; subject M. Average  $\beta$  (3 experiments) 14.5; subject C. Average  $\beta$  (2 experiments) 17.9. The average of all the above experiments was a  $\beta$  of 15.5. These tests were all made between two and three o'clock in the afternoon and, so far as possible, under uniform general conditions. No two tests on one subject were made on the same day.

In comparison with the above results on human subjects we have the following observations on experimental animals: Frog's gastrocnemius, stimulated through the sciatic (Martin, unpublished) average  $\beta$ , 20 cases, 0.84; frog's gastrocnemius, uncurarized, stimulated directly,<sup>1</sup> average  $\beta$ , 19 cases, 7.0; frog's gastrocnemius, curarized, stimulated directly, average  $\beta$ , 4 cases, 11.0; frog's sartorius, uncurarized, stimulated directly, average  $\beta$ , 4 cases, 7.0; frog's sartorius, curarized, stimulated directly, average  $\beta$ , 2 cases, 9.7. E. L. Porter<sup>2</sup> reports the following observations on cats: Threshold for wrist extension from stimulation of radial, average  $\beta$ , 14 cases, 1.4; threshold for reflex flexion of hind leg from stimulation of tibial, average  $\beta$ , 17 cases, 2.7. L. B. Nice in the course of a research not yet finished has obtained for the threshold of contraction of the diaphragm from stimulation of the phrenic in cats and rabbits an average  $\beta$  for 15 cases of 1.79.

That the results on man, reported above, represent probably a reasonably close approximation to the actual threshold for individual receptors, is indicated by the results of a series of experiments in which the platinum wire electrodes described on p. 195 were applied to the lip. In these experiments, although the tissue resistance was much higher than in the

<sup>1</sup> Published in part, 'Measurement of Induction Shocks,' p. 86.

<sup>2</sup> E. L. Porter, *American Journal of Physiology*, 1912, XXXI., p. 148.

experiments with needle electrodes thrust through the skin, averaging 31,000 ohms for the lip electrodes as compared with 10,000 ohms for the needles through the skin, the average  $\beta$  was virtually the same, 16 for the lip stimulation, as compared with 15.5 for the needles through the skin.

If we assume, as we probably may with justice, that the threshold for electrical stimulation of the tongue is substantially the same as that just reported for the lip, we may say in general terms, that a barely perceptible stimulus on lip or tongue is ten to twenty times as strong as the threshold for direct stimulation of the nerves of experimental animals, and twice as strong as the threshold for direct stimulation of frog's muscle.

*The Sensory Threshold an Index to the General Irritability of the Subject.*—In our experiments with electrodes of salt solution in which the fingers were dipped (p. 196) the conditions differed from those obtaining in our experiments with the other types of electrodes described, in two important particulars; the current was much more diffuse, and instead of being confined chiefly to the skin in the immediate neighborhood of the electrodes, was obliged to penetrate a considerable mass of underlying tissue. That the values of  $\beta$  given with these electrodes would differ widely from those yielded by the needle electrodes was to be anticipated. The liquid electrodes, have the advantage, however, of greatly lessened tissue resistance, and of less disturbing influence on the subject, in this latter respect proving far superior to the other types tested by us.

Our results with these electrodes are interesting for their uniformity. Early in our use of liquid electrodes it became evident that the values of  $\beta$  given by them in normal human subjects vary to a surprisingly moderate degree. This uniformity is dependent, of course, upon similarity of experimental conditions. Thus all readings were taken in the afternoon and whenever possible between two and three o'clock. The subject sat alone in a room, and concentrated his attention upon the fingers undergoing stimulation.

Our first series of experiments gave the following average



values of  $\beta$ : Subject P, average  $\beta$ , 13 experiments, 105; subject N, average  $\beta$ , 15 experiments, 113; subject M, average  $\beta$ , 15 experiments, 99.5. The general average of all these observations is a value of  $\beta$  of 106. With one of the subjects, P, the value of  $\beta$  from January 30 to February 8 did not drop below 100 and did not exceed 115.

Another series of observations was made upon a subject, L, through the kindness of Dr. F. G. Benedict, director of the nutrition laboratory of the Carnegie Institution of Washington. These readings were taken in the nutrition laboratory between 4:00 and 5:00 P. M. The average  $\beta$  of six readings was 120, the extremes were 112 and 130. A single reading upon another subject, O'C., taken at 4:00 P. M. gave a  $\beta$  of 97.

Mr. G. P. Grabfield in the course of acquiring mastery of the method for use in another research has made a number of single determinations of  $\beta$  on different individuals. He has kindly permitted the results of these determinations to be incorporated here. The values of  $\beta$  are 102, 72, 72, 110, 76, 119, 75, 82. Not all these readings were taken at the same time of day, and are not, therefore, to be compared so strictly as the results of our earlier series. They are significant, however, as showing that valid determinations can be made upon subjects who have not had previous experience in the use of the method, and also as additional evidence of the substantial uniformity of the sensory threshold when determined with liquid electrodes.

*Receptors Affected by Electrical Stimulation.*—A question of interest in connection with our studies of sensory electrical stimulation is as to the nature of the receptors affected by the electric shock. Thunberg, in his paper on the cutaneous senses, in Nagel's 'Handbuch der Physiologie' (1904, III., p. 698) includes electrical stimuli among those arousing pain. Our observations are in accord with Thunberg's classification, so far as concerns the method of stimulation in which needle electrodes are thrust under the skin. Our subjects were agreed that the only sensation given by electric shocks through these electrodes was pain, whether the stimuli were just at the threshold or considerably above it.

When wire electrodes pressing against lip or finger tip were used, there was equal agreement that stimuli at or just above the threshold aroused no pain sensation whatever, although stronger stimuli were undoubtedly painful. All our subjects described the threshold shocks as resembling touch. To test further the accuracy of this classification we arranged a pair of finger tip electrodes so that one of them could be moved slightly, altering the pressure against the finger. None of the subjects could distinguish any difference in quality between threshold electric shocks and the gentle pressure of the moving electrode.

Experiments with the liquid electrodes were performed on many more subjects than were experiments with the electrodes of the other types described. We made a practice of asking subjects to observe their sensations and to report them. Not a subject suggested that threshold shocks administered through liquid electrodes contained any painful quality. There was, naturally, considerable vagueness of description from those subjects who had had no experience in psychological experimentation. Fortunately several of our subjects had served formerly as subjects in psychological experiments. These gave such reports as that the sensation produced by the electric shock resembled the sensation which accompanies involuntary fluttering of the eyelid; or the sensation given when a finger is pulled till the joint cracks; or the sensation accompanying slight twitching of a muscle. From these reports, in view of the entire absence of definite conflicting observation, we consider it possible that the sensation aroused in this case is of muscle or joint sense.

A comparison of the methods of applying the stimuli affords ground for believing that the different types of electrodes may well stimulate different receptors. The current from the needle or wire electrodes is rather sharply localized, and would be expected to stimulate superficial receptors. The current from the liquid electrodes, on the other hand, is not only more diffuse, but also in its course penetrates more or less deeply the subcutaneous tissues, and might easily stimulate receptors of deep sensibility.

It is possible that the much higher threshold for stimuli applied through liquid electrodes, as compared with those sent in through needle or wire electrodes, is to be explained in part, at least, as due to the different receptors affected, and not wholly to the greater diffuseness of the current. Some incidental observations made in the course of this investigation lend support to such an idea. One of the subjects had on one of the days of experimentation a small cut on one of his fingers, and when that finger was used as one of those to be immersed in the electrodes the surprising result followed that the threshold was very much lower than the usual value. There was at the same time a marked change in the quality of sensation, each shock producing a distinct throb of pain, even at the threshold. At once after determining the threshold for the sore finger it was replaced by a sound finger and the threshold again determined. The painful quality was no longer manifest. The thresholds, in  $\beta$  units, were, for the sore finger 12; for the sound finger 88. To corroborate these observations another subject cut away, with a sharp scalpel, the superficial layers of skin from a small area of one finger, until great tenderness developed, but without bleeding. When stimuli applied through this finger were compared with those through sound fingers precisely similar observations to those reported above were made; there was pain felt in the sore finger at each stimulus, but not in the sound finger, and the threshold was much lower for the sore than for the sound finger. The figures for  $\beta$  were, in this case, respectively 44 and 105. Comparison of the values of  $\beta$  for sore fingers with the values for cutaneous stimulation given on page 201 show that they approach each other closely. In these experiments the general conditions were identical. Tissue resistance was unaffected by the small sore on the skin. The current must have been as diffuse in one case as in the other. A possible way to explain the result is by supposing the observed threshold with liquid electrodes to represent the true threshold for deep sensibility, and the relation of the cutaneous receptors to diffuse electrical stimulation such that they are unaffected by it unless through injury to the overlying protective skin they are made susceptible to it; in which case they respond at the threshold normal to them.

## SUMMARY

1. Determinations of human sensory thresholds for induction shocks were made with three forms of electrodes: *a*, wire electrodes pressed against the upper lip; *b*, needle electrodes thrust through the superficial layers of skin of the finger tip; *c*, liquid electrodes (sodium chloride solution) into which two fingers were dipped.

2. It was shown that a valid measure of the sensory threshold may be had in terms of  $\beta$  units; inasmuch as concordant values of  $\beta$  were given in repeated determinations of the sensory threshold notwithstanding wide variations in tissue resistance and in the contact of the stimulating electrodes.

3. When the stimulus was applied by means of needle electrodes thrust through the skin an average sensory threshold of 15.5  $\beta$  units was obtained. With wire electrodes pressed against the lip, the average threshold was 16  $\beta$  units. These values, compared with thresholds of 0.84 for frog's sciatic, 1.4 for cat's radial, 1.79 for mammalian phrenic, 7 for frog's muscle, uncurarized, and 10-11 for frog's muscle, curarized, suggest an electrical sensibility for the human skin fifty per cent. less than for frog's muscle, and one tenth to one twentieth that of naked nerve.

4. The human sensory threshold, measured with liquid electrodes, averages a value of 100  $\beta$  units, ranging between 70 and 130. So constantly and in so many different subjects have thresholds fallen within this range that we conclude it to represent the normal for this method of stimulation.

5. The testimony of the subjects of these experiments as to the nature of their sensations under liminal electrical stimulation suggests that with needle or wire electrodes applied to the skin cutaneous receptors may be the ones affected; whereas with liquid electrodes the receptors to respond may be those of deep sensibility.