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ELECTRICAL TESTS OF SENSATION *

Voltage-Duration Curves of Tactile Sensation and Pain

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Therapeutic use of stimulating currents is often seriously limited by the pain or discomfort produced by the stimulus. The experiments to be reported are preliminary studies of the problem of combining maximum muscle contraction with minimum pain and deal with measurements of tactile sensation and pain produced by passage of an electric current.[1]

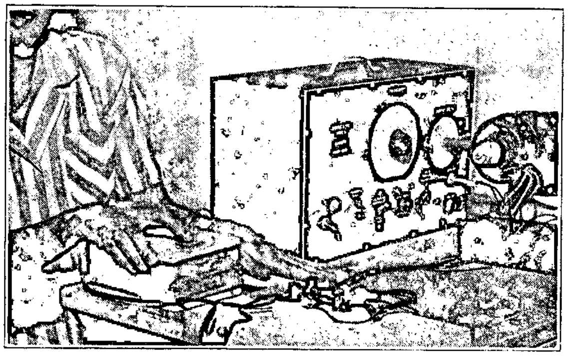

Fig. 1. — Method of testing tactile threshold and maximal pain.

Methods

The technic used in most of the experiments on tactile threshold and maximal pain threshold was the following. The output of a Grass Model 3 Square-Wave Generator (output impedance, 500 ohms) was led into the subject through a large indifferent electrode of cloth-covered metal foil, measuring 10.5 by 15 cm. over which the moistened left palm was placed (fig. 1). The right forefinger, also moistened with electrode paste, pressed on a small electrode, measuring 2.4 cm. in diameter, similarly cloth-covered and arranged to start the current flowing from the generator as the circuit was completed through the patient. Simultaneously with closure of the circuit, a small direct current motor geared down to 5 revolutions per minute turned the voltage control potentiometer. The stimulus to the subject was thus slowly built up at a constant rate. The subject was instructed to jerk his finger tip off the small electrode the instant he felt the slightest tickle or change in sensation or, alternately, when he was feeling maximal pain, which he could no longer bear. A reversing switch in the field of the motor was used to return the potentiometer to zero setting. Motor or sensory determinations could be made while varying the frequency (repetition rate) of the mono-

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* Dr. Rose was formerly Baruch Research Fellow in Physical Medicine, Massachusetts General Hospital, and Dr. Mead was formerly Baruch Fellow in Physical Medicine, Harvard Medical School and Massachusetts General Hospital, and Research Fellow in Medicine, Harvard Medical School.

[1] In these experiments a wide variety of current sources, wave forms and measuring devices have been used. Standard radio resistors and capacitors were employed in the various circuits. Many types of electrodes were used, including the standard cloth-covered lead foil moistened and covered with electrode paste, solder buttons, needles and Lucite cups.

phasic square waves as well as their duration (range 0.05 to 20.0 milliseconds).

In the square wave experiments the output voltage of the stimulator was recorded at the instant the subject broke the circuit. At this point the direct current motor stopped turning the voltage potentiometer. Its inertia introduced a small constant reading error, into which was also lumped the patient's central reaction time.

The subjects were all young, healthy adults, about one third male and two thirds female. The same instruction was given to all. Due attention was paid to the distracting factors considered by Wolff and Goodell[2] which introduce errors into sensory testing. The subject was seated where he could not see the dial markings. An average of three to five readings was recorded as the end point for each pulse duration.

The values found are highly arbitrary and are dependent on experimental conditions, such as the speed of the direct current motor turning the potentiometer, the actual skin surface in contact with the electrodes and the degree of skin hydration, to mention but a few. In general, the instrumentation error for a single experiment was well inside the variations of psychophysiologic choice, which we estimated at ± 10 per cent.

No attempt was made to measure apparent skin resistance because, as shown by Lebel,[3] this involves many fallacies: If one uses a direct current system, there is a change in skin resistance with both voltage and time. With alternating current systems the resistance depends on the voltage and frequency used but not on the time that the current flows. Further, it is not certain that data obtained when one kind of stimulus or current is used can be applied to problems in which a different kind is used. For these preliminary experiments it was found impractical to measure the voltage drop across or current through the load.

Results

A. Sensory Experiments with Sine Waves. — Maximum pain only was tested. Within the limitations of the power output available, the frequency spectrum from 20 to 3,000 cycles per second was explored. Figure 2 shows the type of curve obtained. The abscissa in this figure represents frequency in thousands of cycles per second. The power output was inadequate for a complete motor chart, but such curves have been constructed by Coppee,[4]

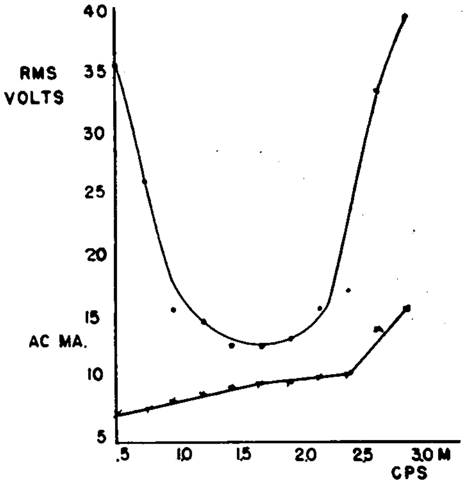

Fig. 2. — Sensory tests with sine waves. The end point registers maximum pain; the upper curve represents voltage and the lower curve current.

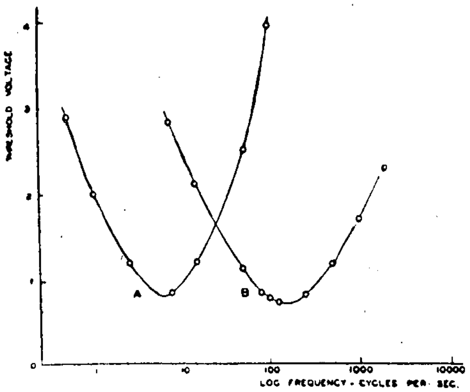

Fig. 3. — Motor charts. *A*, for foot muscle of a snail; B, for sciatic nerve of a frog.

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[2] Wolff, H. G., and Goodsell, H.: Relation of Attitude and Suggestion to Perception of and Reaction to Pain, A. Research Nerv. & Men. Dis., Proc. (1942) 23:434, 1943.

[3] Lebel, Claude: Personal communication to the authors.

[4] Coppee, G.: Une nouvelle caractéristique chronologique de l'excitabilité: la fréquence isopotentielle, Arch. internat. de physiol. 38:251, 1934.

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as illustrated in figure 3. Curve *A* is for the foot muscle of a snail, and curve *B* is for the sciatic nerve of a frog. The resemblance to our sensory measurements is striking.

The question of what component of a sinusoidal electric discharge is most responsible for the production of pain naturally arose. A complete answer to this question cannot be given, but at least voltage and power do not seem to be the answer. For a constant end point of maximum pain, the only other curve approaching constancy for most of its length is the current (lower line, fig. 2). For the square wave experiments insufficient data are available to permit comparison.

B. Sensory and Motor Voltage-Duration Curves. — With use of square waves as the stimuli, a comparison of the voltage-duration curve of maximal pain and a previously agreed on standard motor contraction was made. The standard motor contraction was, for purposes of this experiment, defined as that degree of contraction by which the tip of the finger barely touched the thenar eminence when the third or fourth slip of the flexor digitorum profundus muscle was stimulated percutaneously over its motor point. Later in the course of the experiments minimum sensory (tactile threshold) was added. Minimum pain, or pain threshold, was found to be an unreliable and inconstant end point, but maximum pain was repeatable often within 1 volt.

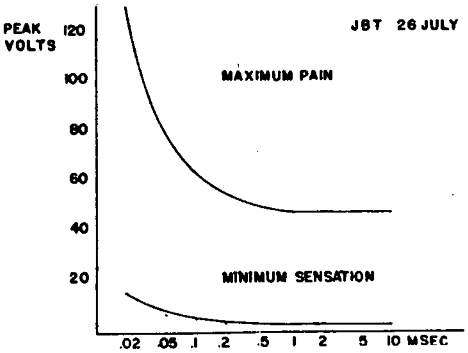

Fig. 4. — Typical curves with maximum pain and minimum sensation.

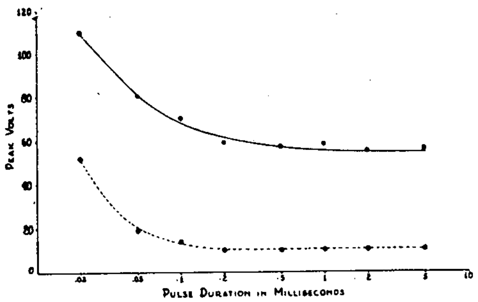

Fig. 5. — Typical normal sensory-motor strength-duration curves. Upper curve, maximum finger tip pain; lower curve, standard motor contraction (flexor digitorum profundus).

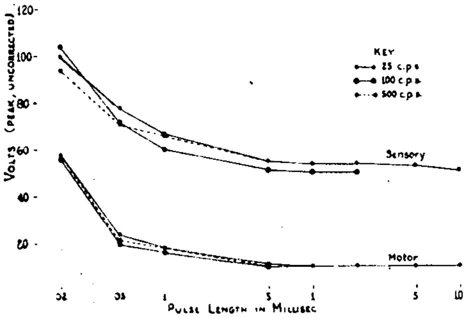

Fig. 6. — Frequency effect on pain maximum and standard motor contraction.

Figure 4 illustrates the type of curve with maximum pain and with minimum sensation. The duration of each stimulus in milliseconds is plotted on the logarithmic grid. The frequency of stimulation was 100 cycles per second. Very similar curves for minimal sensation were obtained when condenser discharges were employed as the stimulus.

Figure 5 shows the comparison on another subject between maximum pain and standard motor contraction. The similarity between this and the preceding figure is apparent.

The effect of varying the frequency of the square wave stimulation was determined. With the frequencies available (20 to 500 cycles per second) no significant difference were noted on either the motor or the sensory end points. One merely obtained a family of close fitting curves (fig. 6). In all subsequent experiments the frequency was arbitrarily set at 100 stimuli per second.

The effect of changing the site stimulated was then investigated. Considerable changes, both qualitative and quantitative, were encountered. The palm tolerated much more energy than the finger tip, and the base of the finger was intermediate. Bony prominences, such as the ulnar styloid, were more sensitive than fleshy areas. While deep, throbbing, sometimes cutting or aching pain was usually experienced in the hand, the skin of the forehead felt a purely burning type of pain, exactly like that produced by a hot lamp. This latter site could not be used because of flicker from optic nerve stimulation, which tended to distract the subject. Because of the ease with which results could be duplicated, the finger tip of the index or third finger was used for these experiments.

Although the results during any given experiment were highly consistent, it was found that there was considerable variability in the same subject over a period of days. To test this variability, fifteen daily determinations were made under comparable environmental conditions on a 36 year old subject; the extreme variations from the mean were 75 per cent for the sensory rheobase and 42 per cent for maximum pain. In 24 young adults, mostly women, the mean sensory rheobase was 5.75 volts and 31 volts for maximum pain; extreme variations amounted to 52 per cent of the mean.

Minor differences were found when different fingers or the left hand was substituted at the small electrode, when the square waves were inverted and when the determinations began at one end of the scale of pulse durations rather than the other.

Comment

Few studies of electrically produced pain are available in the literature. The older European literature on the subject, much of it unavailable, has been summarized by Neoussikine and Abramowitsch.[5] Faradic currents were usually employed and two thresholds described, minimal sensation (*Kribbeln*) and minimum pain. The difference between these values was called the faradic interval, and it was supposed to be altered in a constant fashion in various diseases of the nervous system. Stimulation of metal tooth fillings with a galvanic current by Eddy[6] at the National Institute of Health has given inconstant results. Lanier[7] found marked variations in pain thresholds with use of constant current and bipolar stimulation. However, electricity seems admirably adapted to problems of this kind because of precise methods of measurement, small size of apparatus required and ease of control.

Strength-duration curves of sensation are probably not new, although few references can be found in the literature. Bourguignon[8] mentioned sensory chronaxie determinations but gave no details.

The significance of the strength-duration relation for motor nerves has been discussed by A. V. Hill,[9] who from certain acceptable assumptions regarding the excitation state of muscle derived mathematically a formula and

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[5] Neoussikine, B., and Abramowitsch, D.: Elektrodiagnostik, Bern, Hans Huber, 1939, p. 203.

[6] Eddy, Nathan B.: Personal communication to the authors.

[7] Lanier, L. H.: Variability in Pain Threshold, Science, 97:49, 1943.

[8] Bourguignon, G.: La chronaxie chez l'homme, Paris, Masson & Cie, 1923, p. 399.

[9] Hill, A. V.: The Strength-Duration Relation for Electric Excitement of Medullated Nerve, Proc. Roy. Soc. London, S. B. 119:440, 1936.

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a theoretical curve to express this relationship. The formula is a complicated exponential having the general form of a condenser discharge. This theoretical curve has been found to fit closely the experimental values in motor nerve excitation. The similarity of the values for motor nerve excitation to our findings for sensory stimulation is apparent. It may be concluded then that sensory and motor nerve excitation are essentially similar processes with respect to the time-intensity relation.

That the strength-duration relation holds for other types of energy than electric currents is suggested by curves published by Bigelow, Harrison, Goodell and Wolff.[10] The form of the curve is the same as illustrated in figure 5, although the stimulus used by the authors cited was radiant energy (heat) and the time relations are in terms of seconds rather than in milliseconds.

It is important to note that the pain end points described do not correspond with threshold pain and reactive pain determined on the Wolff Hardy apparatus.[11] Threshold pain was found to be indeterminate, as was previously noted. Reactive pain — i. e., wincing, frowning, withdrawal, etc. — sometimes occurred an appreciable time before the subject took his finger off the electrode. In other subjects such reactions were never noted at all or could be suppressed. Maximal pain could not be suppressed, and interruption of the circuit at this point was almost an involuntary act.

From experiments with radiant energy, Hardy, Wolff and Goodell[12] concluded that spatial summation of painful stimuli does not occur in the skin. In our experiments the area stimulated could not be changed without changing current density; hence this observation could not be checked.

We are unprepared to say whether the maximum pain end point represents a stimulation of fast ($^{\delta}$ fiber) pain or slow (C fiber) pain or a combination of the two. It is hoped that future investigation will bear on this point.

It is likely that fluctuations in skin impedance from day to day are in part responsible for shifting values in an individual subject. On the other hand, maximum tolerable pain may itself have a periodic character, analagous to the phasic variations in respiration, blood pressure and many other bodily functions. When more complete data are available, many applications to research and clinical work suggest themselves.

Summary

Experiments are described in which quantitative measurements of electrically produced tactile sensation and maximum tolerable pain were made.

Frequency distribution and voltage-duration curves using these end points were constructed and found to resemble closely similar determinations on motor nerves or nerve-muscle preparations.

Highly consistent results were found in individual experiments, but considerable variation was encountered in a single subject from day to day.

The reduction of a subjective sensation to the objectivity of a voltage-duration curve suggests this method to be worthy of further investigation

Discussion

Dr. Carl L. Levenson (Chester, Pa.): The authors of this paper are to be congratulated upon the development of an original and simple investigative approach to the very complicated problem of pain. This work is a pioneering attempt in physical medicine and it gives us a new tool for further exploration of pain. Its advantages over the older technic of studying pain; the thermal technic of Wolff, Hardy and Goodell; the pressures technic, and some of the chemical technics used in the past are ob-

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[10] Bigelow, N.; Harrison, I.; Goodell, H., and Wolff, H. G.: Studies on Pain; Quantitative Measurements of Two Sensations of the Skin, with Reference to the Nature of "The Hyperalgesia of Peripheral Neuritis," J. Clin. Investigation 24:503, 1944.

[11] Chapman, W. P., and Jones, C. M.: Variations in Cutaneous and Pain Sensitivity in Normal Subjects, J. Clin. Investigation 23:81, 1944.

[12] Hardy, J. D.; Wolff, H. G., and Goodell, H.: Studies on Pain: A New Method for Measuring Pain Thresholds: Observations on Spatial Summation of Pain, J. Clin. Investigation 19:649, 1940.

vious. Not only does this method reduce the number of variables with which the observer has to contend, but it reduces the study to pain itself. It eliminates such factors as fear and other reactions to pain.

The possible scope of this work is as broad as the subject of pain. It opens up a new avenue of approach, although the observers were particularly interested in specific aspects of pain. It seems to me that further study with this type of instrumentation might yield information for the development of apparatus for painless muscle stimulation as well as facts about pain itself. It also could be used possibly for a more critical study of the effects of analgesics.

The technic is very simple. The apparatus is simple. The patient is asked to keep a finger on a button and at the moment of maximum tolerance of pain remove the finger; the circuit is broken, and one has a reading. The element of fear and the patient's conscious collaboration are removed.

I should like to raise a question of which I am certain the authors are cognizant. What is the mechanism by which electrical stimuli produce pain? Secondly, I should like to see them correlate certain basic factors regarding electrical stimulation and occurrence of pain — such as, not only the voltage and the square of the current, but also the duration and frequency of current application. I, and I think others in this room, would appreciate having the authors continue further explorations in this field. I believe that they have made a valuable contribution, and that they will make other contributions of great value if they continue their studies.

PASSIVE MUSCULAR EXERCISE *

MAX A. LEVINE, M.D.

LOS ANGELES

I am presenting a concept of regulated passive muscle stretching which has afforded very satisfactory results. In the past ten years this method of postimmobilization management has been of inestimable value. There is no question in my mind that many of you have employed one form or another of passive stretch or exercise in the follow-up of prolonged immobilization after a cast or some form of traction. The purpose of this paper, however, is to present a technic with special reference to an apparatus which has proved to be invaluable in my practice. This equipment could easily and inexpensively be installed in any orthopedic office or department of physical therapy in a hospital. It consists of a modified ratchet-controlled windlass capable of exerting a considerable pull (figs. 1 and 2). The exact force of this pull is checked by a scale which is interposed between the patient and the table (stretching apparatus) (fig. 3).

In view of the fact that the results were so uniformly satisfactory in private practice a duplicate of this apparatus was made and used in the Army hospital where I was stationed. It is obvious that if those soldiers with severe disability due to very serious injury as well as prolonged immobilization were benefited by use of the apparatus, its merits are well founded.

We are all cognizant of the fact that in an injured extremity after prolonged immobilization a considerable number of adhesions will develop. The longer these are allowed to remain, the denser they become. The pathologic changes which occur in soft tissues as a result of trauma and immobilization may be summarized as follows: There is usually a hemorrhagic exudate of varying degree into the muscles and areolar tissue at the site of trauma. Inflammatory exudate and edema fluid extend for considerable distances into the adjacent soft parts and often involve the whole extremity. This is the

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* From the Department of Orthopedic Surgery, Cedars of Lebanon Hospital.

* Read at the Western Orthopedic Association, Nov. 6, 1947, and the Western Hospital Association, April 21, 1948, Los Angeles.