Cutaneous Vibratory Thresholds for Square-Wave Electrical Pulses

One approach to the understanding of the cutaneous senses is the study of their responses to stimulation by electric currents. If the several senses show different effects of variations in stimulus current parameters, this might help to elucidate the mechanisms involved.

As the frequency of alternating current applied to the skin is increased, there is a rise in thresholds for sensations of vibration (or "tingle") (*1*, *2*) and of pain (*3*), the latter thresholds rising at a somewhat greater rate than the former. These effects could result from such factors as the change in frequency, the change in rate of current increase during an individual cycle, or from the change in duration of each cycle. All these quantities change as the frequency of sinusoidal current is changed, and consequently their effects cannot be assessed separately.

If square-wave stimulation is used, there can be achieved separate variation of frequency and duration, while rate of current increase during each pulse remains constant. Square-wave stimulation is thus a means of analyzing the frequency-intensity functions obtained with sinusoidal currents.

In 1953 Sigel (*4*) published results of stimulation of the upper volar forearm with square-wave electrical currents. It appeared desirable to reinvestigate the matter with several improvements in technique. (i) A stimulator of high impedance was used. Because of the capacitance of the human skin, square-wave voltages applied to it result in the passage through it of currents almost spike-like in form when the source is of low impedance. (The stimulator used by Sigel has an output impedance of 250 ohms.) (ii) The current passed through the skin was measured rather than the voltage applied to it, because of variations in skin impedance during an experimental session. (iii) Psychophysical procedure in threshold measurement was used.

Square waves were provided by a General Radio type 1217-A unit pulser driving a General Radio type 1219 unit pulse amplifier. A 100-kohm potentiometer across the amplifier output provided an adjustable square-wave voltage with which to buck a 45-v cutoff voltage applied to the grid of a type 24-G transmitter triode. The triode plate circuit, operated at 900 v, included in series the subject, a 10-kohm measurement resistance near the electrodes, and 600-kohm of resistance. Current amplitude through the subject was computed from the voltage across the measurement resistance as observed on a DuMont type 340 oscilloscope, calibrated with a DuMont type 264-B voltage calibrator. The diameter of the indifferent electrode was 24 mm; that of the active, positive electrode was 7 mm. Both electrodes were covered with Medcraft electrode paste.

Table 1. Mean absolute thresholds at the several pulse durations and rates. The upper number is threshold in milliamperes; the lower number is the ratio of threshold to mean of all thresholds at 2.0 msec and longer. Entries in parentheses are medians of data from one observer; other entries are means of data from three observers.

Pulses per sec	Pulse duration (msec)							
	0.1	0.2	0.4	0.7	1.0	2.0	4.0	7.0
1000		(1.03) (2.06)	(0.84) (1.68)	(0.81) (1.62)				
500	(1.50) (3.00)	1.25 1.88	0.98 1.47	0.85 1.28	0.85 1.28			
200	(1.40) (2.80)	1.27 1.91	0.97 1.46	0.78 1.17	0.71 1.07	0.66 0.99		
100	(1.50) (3.00)	1.25 1.88	0.97 1.46	0.79 1.19	0.72 1.08	0.63 0.95	0.67 1.01	
60	(1.52) (3.04)	1.37 2.06	1.04 1.56	0.84 1.26	0.75 1.13	0.67 1.01	0.68 1.02	0.69 1.04

Two graduate students and one staff member served as subjects. All had had previous experience in reporting electrically aroused cutaneous sensations. The seated subject placed the heel of his right palm on the indifferent electrode, his right index finger pad on the active electrode, and was told to report the occurrence of vibratory sensations.

Thresholds were measured by a modified method of limits (continuous variation; ascending series only in order to avoid adaptation). Frequencies investigated were 60, 100, 200, 500, and 1000 pulses per second. Pulse durations ranged from 0.1 to 7.0 msec, with the limitation that a duty ratio of 0.5 could not be much exceeded by the pulse amplifier. The longer durations therefore had to be omitted at the higher frequencies. During a given session on a given day one ascent to threshold was made at each of the 30 usable combinations of frequency and duration. A total of eight sessions, on eight different days, took place for each subject. The presentation order of the frequency-duration combinations was scrambled from one day to another.

The resulting eight measurements at each frequency-duration combination were first averaged for each subject. Before the results for the three subjects were combined, the averages were converted to ratios of the individual's baseline, in order to provide measures which were comparable in spite of individual differences in sensitivity. The baseline for each subject was taken as the mean of his thresholds at durations of 2.0 msec and longer, these values being essentially the same for a given subject. The three baselines were 0.50, 0.69, and 0.80 ma.

Table 1 presents the thresholds obtained in terms of current and also shows the corresponding ratios to baseline, the latter being the dependent variable in the strength-duration curves of Fig. 1. The curves for the several frequencies are quantitatively quite similar, indicating that change of frequency has a negligible effect on electrical vibratory threshold. The pronounced effect of pulse duration on threshold is similar to but somewhat greater than that shown by Sigel for 50 "c.p.s." and is quantitatively similar for the other frequencies investigated.

In the range of frequencies examined, it may be inferred that the increase of cutaneous vibratory thresholds, as sinusoidal current frequency is raised, results largely from the shortening of the half-

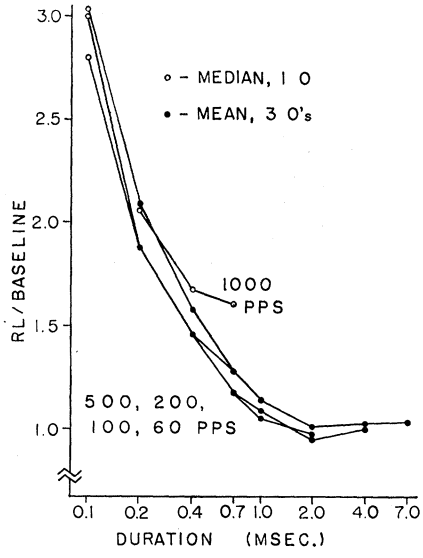

Fig. 1. Strength-duration curves at several pulse rates. "RL/baseline" is the ratio of absolute threshold (RL) to the mean of RL's at pulse durations of 2.0 msec and longer. The parameter is pulses per second (PPS). The means of data from three observers (O's) are indicated by solid circles; at those points for which the RL's of two O's were above maximum stimulator output, the medians of the data for the remaining O are indicated by open circles.

cycle length, rather than from any direct effect of frequency per se. Quantitatively, the effect of halving duration is to double the difference between the absolute threshold and the baseline.

However, it is not clear that duration alone can account for the entire frequency effect in sinusoidal stimulation. At frequencies sufficiently high that the baseline current is a negligible fraction of that required to reach absolute threshold, doubling frequency should double threshold. Schwarz (*2*) found this to occur in the range from 1 kcy to 4–16 kcy/sec (the upper limit depending on certain other parameters), but at higher frequencies (for example, 32 and 64 kcy/sec) thresholds were significantly higher than would be predicted. This might result either from physiological factors such as altered distribution of stimulus current in the tissues, or from increased loss in the stimulating apparatus at high frequencies.

It is of interest that the curves of the present experiment indicate a chronaxie of about 0.2 msec, a value typical of that obtained from A-fibers. Uttal (*5*), reporting an experiment involving the effects of ischemia on thresholds for single electrical pulses applied to the forearm, also concluded that A-fibers were involved in electrical cutaneous sensory stimulation. However, neither experiment necessarily means that "nerve" as opposed to "receptor" is invariably the site of such stimulation. In view of the evidence marshalled by Weddell (*6*) against any necessary morphological distinction between cutaneous sensory nerve and receptor, a more cautious interpretation is indicated. Certain characteristics of the response to electrical stimulation of the "touch" system have been ascertained. It remains to be seen whether the other cutaneous qualities differ in the way in which they respond to changes in stimulus current parameters (*7*).

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References and Notes

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The Molecular Formula Generalized in Terms of Cyclic Elements of Structure

The molecular formulas for all ordinary covalent substances may be generalized in terms of the number of cyclic elements of structure in the molecules according to Eq. 1:

$$\rho = 1 + \tfrac{1}{2} \Sigma n_v (v - 2) \qquad (1)$$

where ρ is the total number of rings and multiple bonds in the molecule (that is, *cyclic structures*), n_v is the number of atoms of covalence v, and the sum is taken over all the v's. The term *cyclic structures* may be used to include both rings and multiple bonds if the latter are considered to be (as they are, indeed, logically, generically, and stereochemically) two-membered rings.

For most organic and inorganic covalent substances, this reduces to Eq. 2:

$$\rho = 1 + \tfrac{1}{2}(2n_C + n_{N,P} - n_{H,X}) \qquad (2)$$

where n_C is the number of carbon atoms in the molecule, $n_{N,P}$ is the total number of nitrogen and phosphorus atoms, and $n_{H,X}$ is the total number of univalent atoms; hydrogen, halogen, and so forth. The terms for oxygen and any dicovalent element obviously disappear. Equation 2 can, of course, be stated also as

$$\rho = 1 + \tfrac{1}{2}(2n_{IV} + n_V - n_{I,VII}),$$

where the subscripts refer to the numbers of the main groups in the Periodic Table.

The single term for all nitrogen atoms regardless of their oxidation numbers or their formal valence numbers follows from the consideration that the cyclic structures containing nitrogen ordinarily involve the three nonpolar bonds and not the additional coordinate bonds present in the higher oxidation state (compare nitroso and nitro groups). Similar considerations apply to the coordinate valencies in oxidized sulfur and phosphorus, but if in these atoms an expanded covalency involving, for example, ten electrons is visualized, the terms $2n_S$ and $3n_P$ would be indicated in Eq. 2.

Electrovalent radicals can be accommodated by reference to their covalent analogs, the free acids and bases; for quaternary nitrogen the term $3n_{N^+}$ based on an empirical pentavalence, applies.

These equations have practical utility in that the number of cyclic structures is given directly by substituting in Eq. 2 the subscripts in the molecular formula —for example, bromine, $Br_2 = 0$; cholesterol, $C_{27}H_{46}O = 5$; hexamethylene tetramine, $C_6H_{12}N_4 = 3$; nitric acid, $HNO_3 = 1$; nitrogen, $N_2 = 2$; nitroglycerine, $C_3H_5N_3O_6 = 3$; penicillin G, $C_{16}H_{17}N_2O_4SNa = 9$; phosphorus sulfoxide, $P_4O_6S_4 = 3$; phosphorus vapor, $P_4 = 3$; streptomycin, $C_{21}H_{39}O_{12}N_7 = 6$; strychnine, $C_{21}H_{22}N_2O_2 = 12$. It is generally accepted tacitly that in counting the number of cyclic structures in a polycyclic system no cyclic structure is counted if it is made up entirely of elements of other cyclic structures which themselves have been counted. That is, decahydronaphthalene, cyclohexene epoxide, acetylene, and nitrogen contain only two cyclic structures each, and tetrahedral molecules, such as P_4, hexamethylenetetramine, P_4O_6, P_4O_{10}, As_4O_6, and $P_4O_6S_4$, contain only three (not four) cyclic structures.

Equation 2 reduces further to the familiar general formulas for the various homologous series of organic compounds if the restrictions which define the series are introduced into it. For example, for the acyclic saturated hydrocarbons (alkanes, paraffins), introducing $\rho = 0$ and dropping terms other than those for C and H gives $n_H = 2n_C + 2$. Similarly, for the homologous amino monocarboxylic acids, introducing $\rho = 1$ and $n_N = 1$ ($n_{oxygen} = 2$), gives $n_H = 2n_C + 1$ ($n_{oxygen} = 2$).

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