U.D.C. 621-05: 62-5
159.938.37:159.935:159.938.253:62.88:007.51

EXPERIMENTS ON THE MAGNITUDE SENSATION OF ELECTROCUTANEOUS STIMULI

by

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ABSTRACT

The subjective magnitude of sensation for electrocutaneous stimuli is experimentally studied.

In experiment I, two pulse trains which have the same pulse interval and stimulus duration but have the different pulse heights (I_A & I_B) and pulse widths (T_A & T_B), have been applied to the skin just above the triceps of a subject via wet electrodes. And tests were made using AB method how various stimulus pairs give the different magnitude sensation or how they give the same magnitude sensation under the various conditions of I_B and T_B for several values of pulse interval as a parameter, while I_A and T_A were fixed to 4.7 mA and 100μs, respectively, as a reference.

In experiment II, the threshold current of minimum sensation for various pulse widths has been examined also by using AB method.

The experimental results suggest that the electrocutaneous magnitude sensation is strongly affected by the energy of one pulse if the pulse width is less than 1 ms and the pulse repetition rate is comparatively low.

INTRODUCTION

Recent interest in improving remote manipulators led to an investigation of methods for transmitting kinesthetic and tactual information from the joints and the hand of the manipulator to the operator through his electrocutaneous sensation. Human characteristics for electrocutaneous stimulation have been studied for the applications to the various fields, e.g. [1,2], such as a tactual vision substitution system [3], improvement of arm prostheses [4], or communication under tasks or environmental conditions which prevent normal communication [5].

For these purposes pulse stimulation is usually chosen, for it is rather comfortably felt and easily controlled than other forms of electric stimulation. And considering from the analogy of hearing, the loudness, pitch and location of the stimuli may be used as carriers of information. Pitch roughly corresponds to the pulse repetition rate (reciprocal of pulse interval), and location corresponds to the positions where the sensations occur. But for the loudness it was not found which parameter, pulse height (current or voltage), pulse width, energy of the pulse, or power, is most relevant. It was also not clear if height and width are independent or not.

In this paper subjective magnitude of sensation for electrocutaneous stimuli is experimentally studied, and the relevant parameter for loudness is sought.

APPARATUS AND METHOD

Apparatus. One channel of the previously designed general purpose simultaneous stimulator system [6] is used. It consists of a digital computer (PDP 11/40), a pulse control unit, and output circuits, and is equipped with 256 output channels. Each channel generates an independent pulse signal, parameters of which, namely, height, width, frequency, and stimulus duration, can be arbitrarily set by the computer program. The maximum speed for refreshing the parameters is 600 [frames/s] when the direct memory access (DMA) mode is used.

Placement of electrodes. The output of the stimulator is isolated by the photo-coupling type isolator (San-ei Instrument Co. 5361), and is presented on to the skin of a subject via wet electrodes (Beckman ϕ 8mm). Three electrodes are located on the skin just above the triceps brachii along the direction of the muscle 20mm apart from each other. The two outer electrodes are connected and used as a common, and the negative pulse is presented to the central electrode (Fig. 1). Electrocutaneous stimulation is provided by a constant current source (CCS). This is because the CCS can present an ideal pulse to a capacitive load like human body, and it is not affected by the change of skin impedance compared to the constant voltage source (CVS) when the impedance is lower (e.g. 1~3 kΩ in case of wet electrodes).

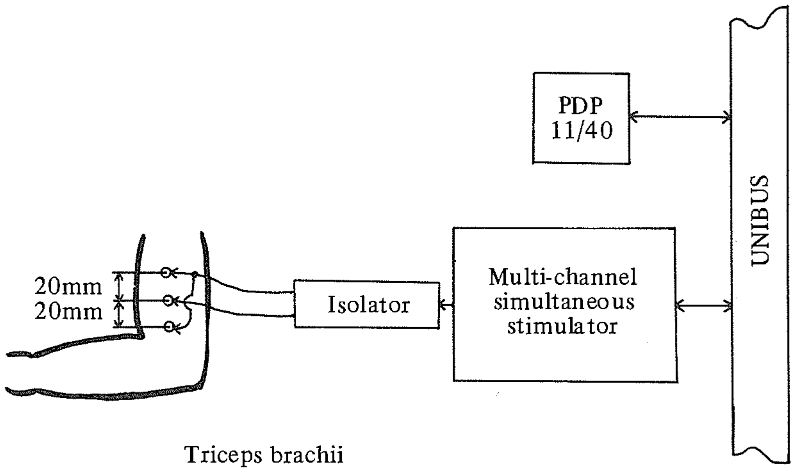

Fig. 1 Schematic diagram of the multi-channel simultaneous stimulator system used in the experiment. Signal parameters, i.e. pulse height, pulse width, pulse interval and stimulus duration, can arbitrarily be set by the program.

Figure 2 shows an example of the current waveform and the voltage waveform across the electrodes during the experiment. The pulse shape of the current remains almost rectangular.

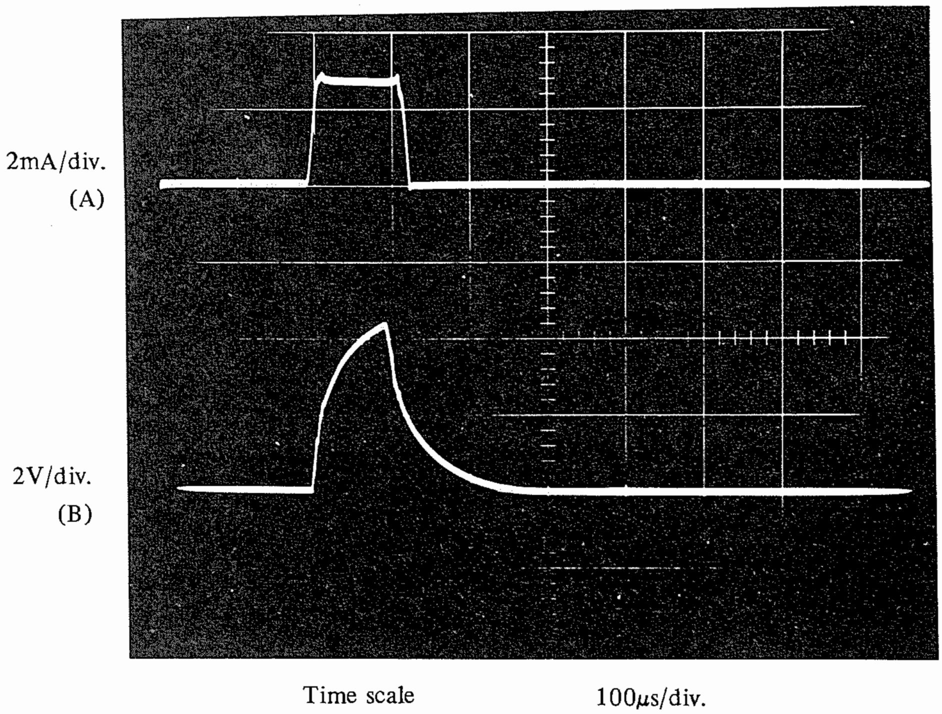

Fig. 2 Current waveform (A) and voltage waveform (B) across the electrodes during the experiment. The pulse shape of the current is almost rectangular, for the constant current source is used.

Subjects. Three subjects of age 21, 22 and 29 were used in the following experiments. One of them is a researcher of experience and two others are students with interest in the experiments.

Test procedure. Two pulse trains which have the same pulse interval and stimulus duration but have different pulse heights (current) and pulse widths are presented to a subject. A subject first feels the two alternatively presented stimuli, which are tentatively named A and B. When he memorized, he presses the keyboard. Then he is presented either of the stimuli randomly and judges which of the two original stimuli he just felt. He judges 50 times for each pair of stimuli, and answers A or B according to his judgement. If we assume that the stimuli A and B are presented equally and randomly, we can get the information transmission rate by the formula of AB method [7],

$$R = 1 + 1/2\ \Big[(p_a + q_b) \log_2 \frac{1}{p_a + q_b} + (p_b + q_a) \log_2 \frac{1}{p_b + q_a} - p_a \log_2 \frac{1}{p_a} - q_a \log_2 \frac{1}{q_a} - p_b \log_2 \frac{1}{p_b} - q_b \log_2 \frac{1}{q_b} \Big],$$

where p_a is the probability of receiving an A when an A is sent, q_a is the probability of receiving a B when an A is sent, p_b is the probaility of receiving a B when a B is sent, and q_b is the probability of receiving an A when a B is sent.

RESULTS

Experiment I

In order to investigate the interference between pulse height and pulse width, two pulse trains which have the same pulse interval and stimulus duration but have the different pulse heights (I_A & I_B) and pulse widths (T_A & T_B) were presented on to the skin just above the tricepts of a subject via wet electrodes. Pulse height had a dimension of current [mA], for the CCS was used.

Figure 3 shows the experimental conditions. The stimulus A was used as a reference. So its parameters, i.e. pulse height, pulse width, pulse interval, and stimulus duration, were first fixed to the values, 4.7 mA [120], 100μs, 100ms, and 2 sec, respectively. The current of 4.7mA corresponds to the D/A conversion value of 120. Since the relative values of current are of importance in this experiment these D/A converter values will be used for convenience.

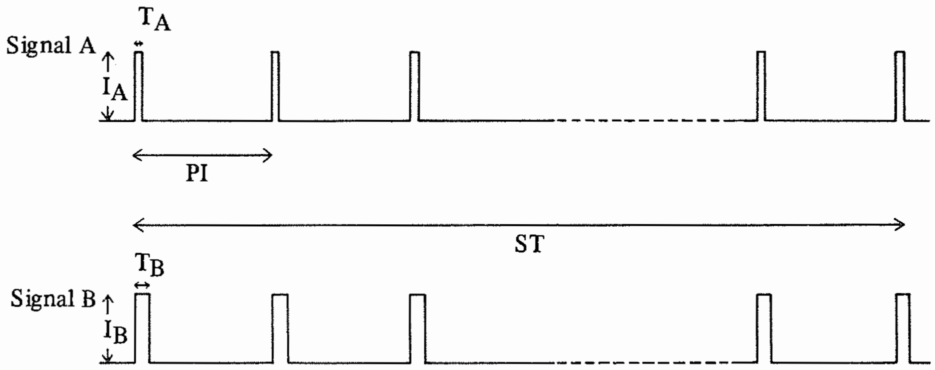

Fig. 3 Experimental conditions. The difference of signal A and B are judged by subjects using AB method. Signal A, a reference, has a pulse height of I_A = 4.7mA [D/A conversion value of 120], pulse with T_A of 100μs, stimulus duration time ST of 2μs. Its pulse interval PI is selected as 100, 50, 20, and 10ms for each round of experiment. Pulse interval and stimulus duration of signal B are always chosen to be the same values of signal A, while I_B is experimentally measured for several values of T_B.

The two parameters of stimulus B, i.e. pulse interval and stimulus duration were always chosen to be the same values as of stimulus A, while the other two parameters, i.e. pulse height and pulse width were differently selected. More specifically, various values of I_B (pulse height of the stimulus B) were chosen for each of about 7 values of T_B (pulse width of the stimulus B).

The stimuli A and B were presented to a subject and compared. And the information transmitted per stimulus was measured by means of the AB method, and used as a measure of the discriminability of the two stimuli.

Figure 4 (A) shows the result for the subject TE. Each mark in the figure is the result calculated from 50 times judgements, and the marks ⊙, △, ⊡, ◇, ∗, X, and • indicate the results for T_B of 150, 200, 250, 300, 400, 800, and 1600μs, respectively. The abscissa represents I_B, and the ordinate represents the information rate, the information about the stimulus differences (bit) transmitted per stimulus.

Information of 1 bit means that we can distinguish the two stimuli thoroughly, while information rate of 0 bit means that the two stimuli are felt the same. As is seen in the figure, the stimulus with T_B of 150μs is completely distinguished from the reference stimulus A when I_B is greater than 110 or less than 70. (When I_B is 120, i.e. $I_B = I_A$, the two stimuli are perfectly distinguished. Since only their pulse widths are different for the case, the difference of pulse width of 50μs is a quantity that can completely be notified.)

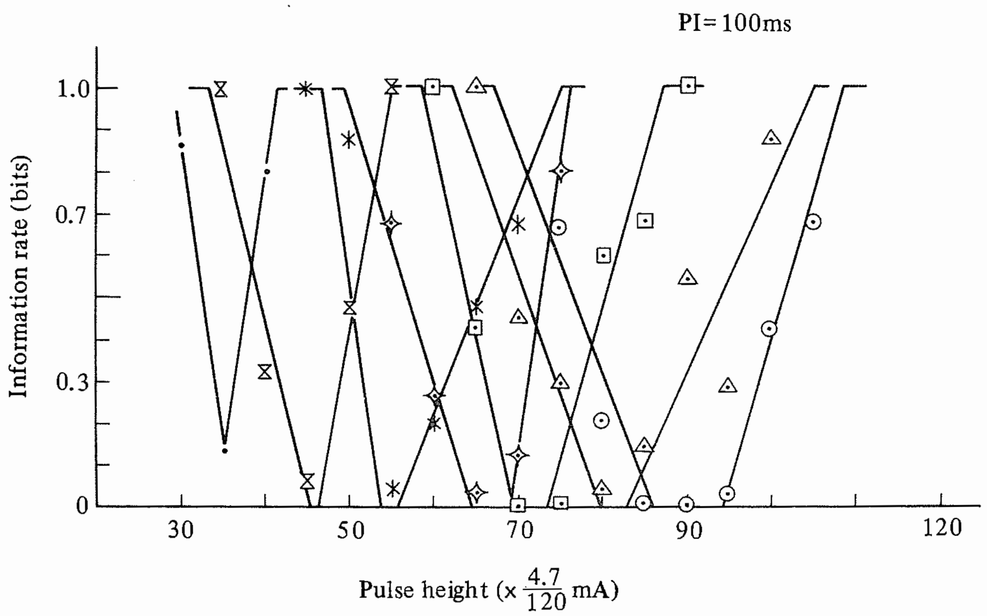

Fig. 4 (A) Detectable difference between A and B of Fig. 3 for PI=100ms. Each mark in the figure is the result calculated from 50 times judgements, and the marks ⊙, ⟁, ⊡, ✧, ✱, ⧗, and • indicate the results for T_B of 150, 200, 250, 300, 400, 800, and 1600, respectively. The abscissa represents I_B, and the ordinate represents the information rate, the information about the stimulus difference transmitted per stimulus. Each mark was obtained from 50 judgements.

But, for the stimulus with I_B of about 90, no difference is notified from the reference stimulus A. These kind of values which give the minimum information transmission rate are about 82, 72, 65, 55, 45, 35, for the values of T_B of 200, 250, 300, 400, 800, and 1600μs, respectively. It is found that for these values the following relation holds.

$$I_B{}^2 T_B = I_A{}^2 T_A.$$

Next, the pulse interval of the reference stimulus A, and accordingly that of B, were changed, keeping the pulse intervals of A and B equal. The same kind of experiments were conducted for pulse intervals of 50, 20, and 10ms. The same tendency is observed for other pulse intervals, especially for PI = 50ms.

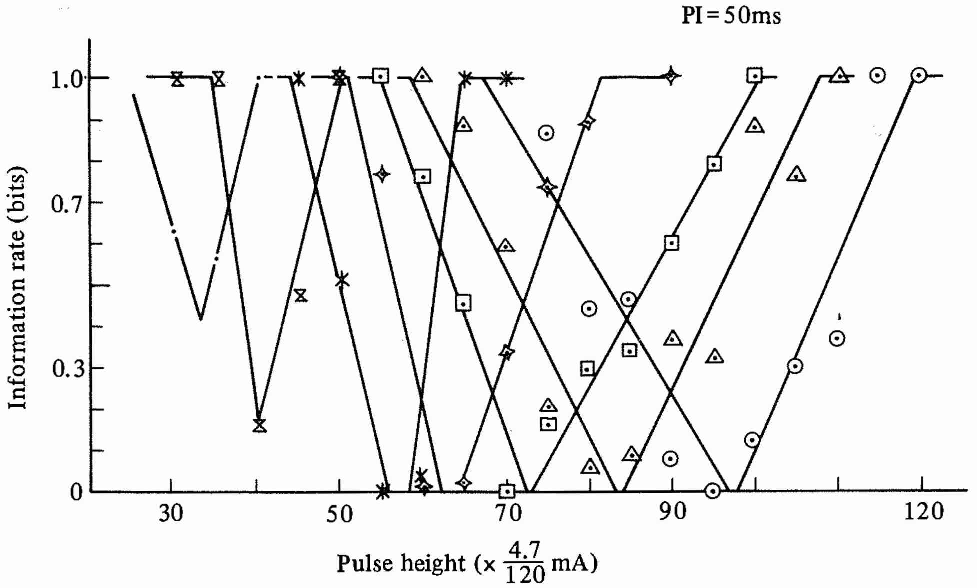

Fig. 4 (B) Detectable difference between A and B of Fig. 3 for PI=50ms.

But, for stimulus pairs with PI of 20 and 10ms the minimum information rate do not reduce to 0 bit. This means that the complete substitution of pulse width by pulse height is impossible for higher frequency pulse stimuli.

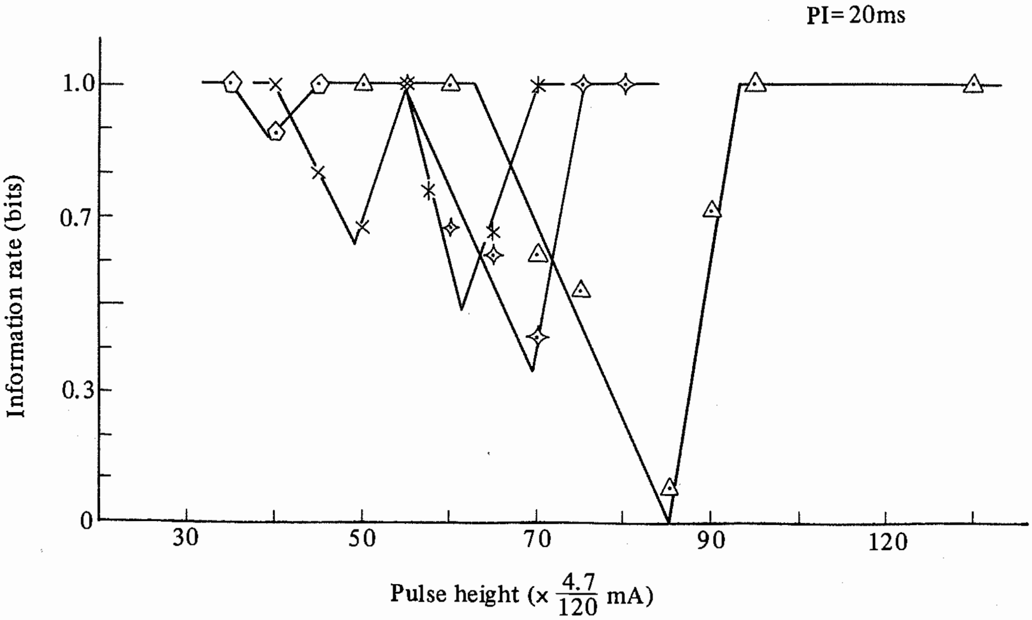

Fig. 4 (C) Detectable difference between A and B of Fig. 3 for PI=20ms.

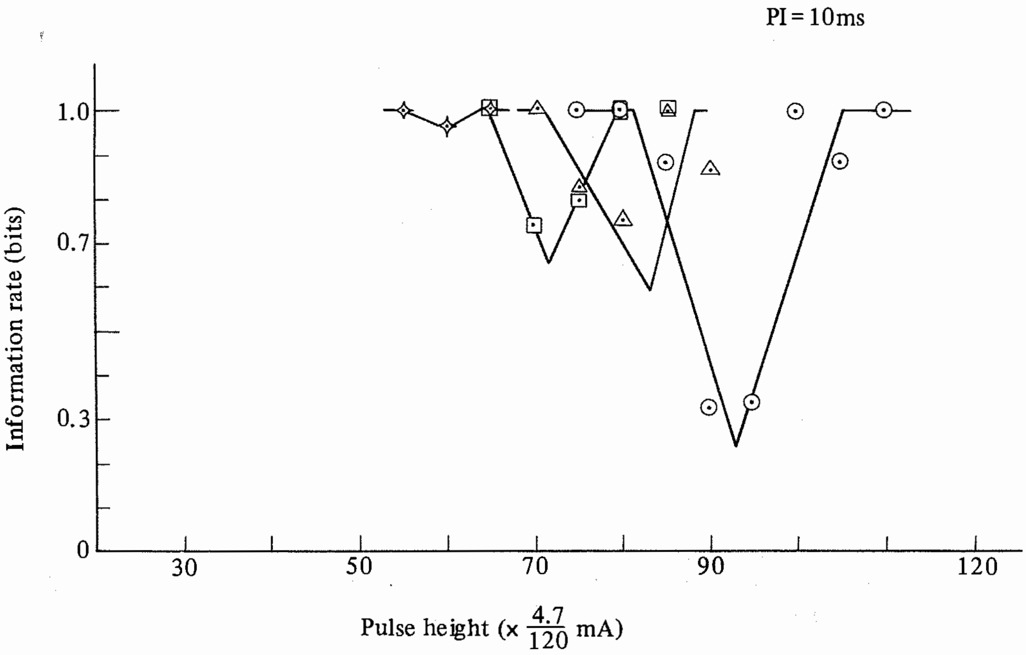

Fig. 4 (D) Detectable difference between A and B of Fig. 3 for PI= 10ms.

Table 1 shows the summary of the pulse height which gives the minimum information rate for three subjects. And in Figure 5 the average values of the three subjects are plotted using a log-log scale. The abscissa represents T_B, and the ordinate represents I_B. The marks ⊙, X, △ and ⊡ are the results for PI = 100, 50, 20, 10ms, respectively. These marks mean that the stimuli with I_B and T_B indicated by their positions have the same magnitude sensation as the reference stimulus.

Table 1 Summary of the pulse height which gives the minimum information rate for three subjects.

Interval (ms)	Pulse width (μs)	150	200	250	300	400	600	800	900	1600
100	TE	90	82	72	65	55		45		35
	JK	95	85	78	65	60	50	45		
	HH	90	80		60	55	45	30		30
50	TE	95	83	71	65	55		42		33
	JK	95	80	78	70	55	50	40		35
	HH	98	80	75	65	55	45			
20	TE		85		68	62	50		40	
	JK	90	80	70	65		53			
	HH	93	83	70	70	55	45	40		
10	TE	93	80	72						
	JK	90	85	72	65	60	50	45		40
	HH	95	80	70						

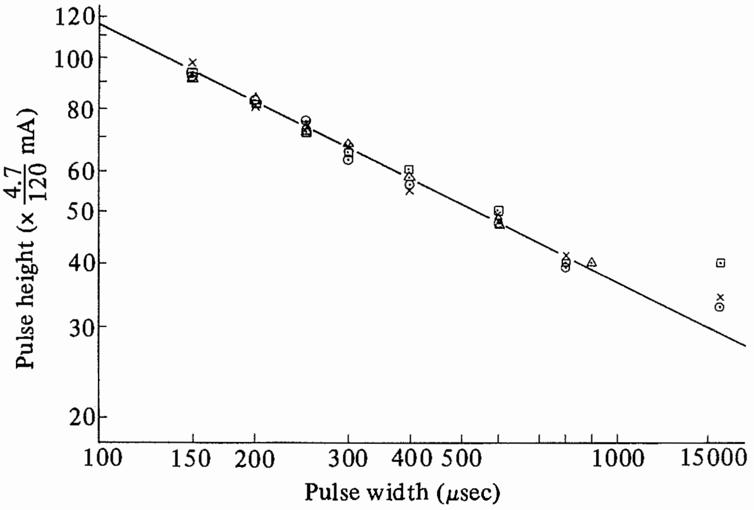

Fig. 5 The average values of I_B that gives the minimum discrimination are plotted using a log-log scale as a function of T_B. The marks ⊙, X, △, and ⊡ are the results for PI = 100, 50, 20, 10ms, respectively. The solid line has a gradient of –0.5.

The gradient of the straight line is –0.5. For the stimuli with $T_B < 1000\mu s$, the mark found just on the line. This shows the relation $I_B = kT_B^{-0.5}$, namely $I_B^2 T_B = c$, more pre $I_B^2 T_B = I_A^2 T_A$ holds (k and c are constants) for the pulse stimuli with pulse width less than 1

From these fact it can be said that the pulse stimuli with the same I^2T give rise the sam jective magnitude sensation when pulse interval is long (low frequency) and pulse width is les $1000\mu s$.

Experiment II

The threshold current of minimum sensation for various pluse width is examined also by AB method. Figure 6 shows the result, where threshold current is measured as a function of width (T). The shape of the curve may be represented by the equation I = a + b/T, as has been tionally done. These data are replotted by using a log-log scale (Fig. 7).

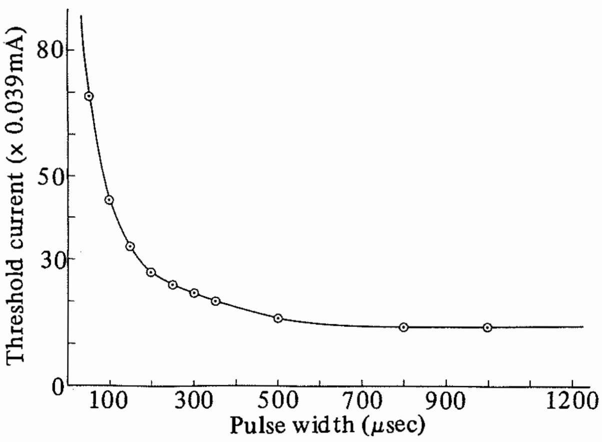

Fig. 6 Threshold current for minimum sensation is measured as a function of pulse width.

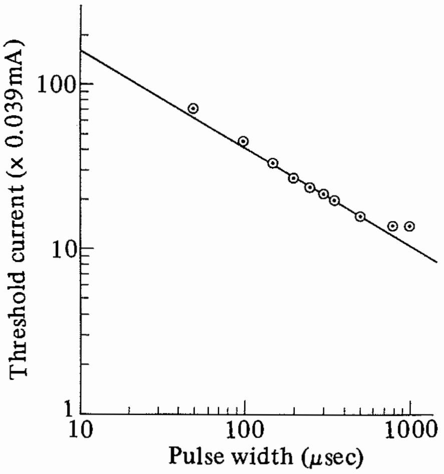

Fig. 7 Replot of the result of Fig. 6 on a log-log scale. The gradient of the solid line is about –0.6.

The gradient of the straight line is –0.6, and almost all points lie on the line, excluding the result for wider pulse width (more than 1000μs).

This result suggests that the threshold of minimum sensation is obtained when the quantity I^2T reaches the same constant value.

Figure 8 shows also the strength-duration data for minimum sensation replotted from the experiment of Reswick et al. [8]. These data are results of the experiment with intraneural electrodes implanted in a below-elbow amputee. The electrodes were placed in the median nerve and in the ulnar nerve. The gradient of the line in Fig. 8 is found to be also –0.6.

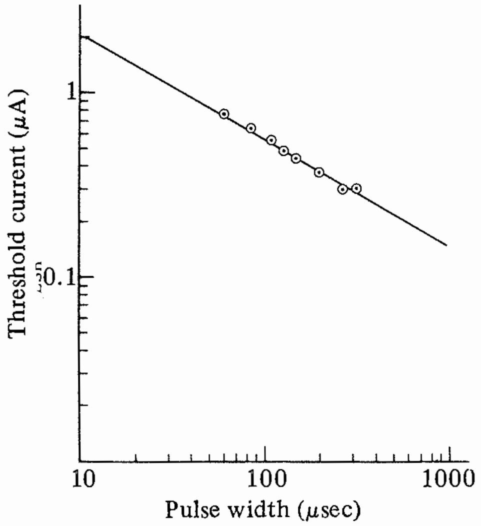

Fig. 8 **Replot of the same experiment as in Fig. 6 by Reswick et al. [8].**

DISCUSSION

The impedance of skin and tissue are thought to remain constant during relatively short period as one round of the experiments (training and 50 times judgements). So the condition under which the same magnitude sensation occurs, i.e. ${I_A}^2T_A = {I_B}^2T_B$, may be interpreted as follows:

$$Z{I_A}^2T_A = Z{I_B}^2T_B,$$

where Z is the impedance of the tissue.

The quantity ZI^2T is an energy consumed in a body. More precisely, the condition might be:

$$\int_0^T Z\cdot i_A(t)^2\,dt = \int_0^T Z\cdot i_B(t)^2\,dt,\ T < 1000\mu s.$$

So it is easily imagined that energy modulation may provide an effective way of transmitting information.

The problem is that since it is difficult to measure the impedance of the tissue, we must estimate it by the impedance measured from the voltage across the electrodes.

We are now investigating human characteristics for constant energy stimulation using the energy measurement instrument.