Perceived Locus and Intensity of Electrocutaneous Stimulation

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***Abstract*—Two experiments investigated perceived locus and intensity for electrocutaneous stimulation. In Experiment 1, 21 subjects reported the perceived locus for various combinations of four electrode sites, two current directions, two pulse characteristics (single versus multiple), and two sensation levels (detection versus pain). In Experiment 2, 16 subjects reported the perceived locus and intensity for a wide range of current levels and two polarity conditions. The main results were 1) sensations were likely to be perceived under the cathode at detection levels, but under both electrodes at intense levels; 2) the "cathode" localization was gradually supplanted by "both" ("anode" and "cathode") localization with increasing current; 3) subjective intensity under the cathode was greater than that under the anode; 4) the effects of cathode position on perceived locus were found for only some pairs of electrodes. These results challenge the simple hypothesis that electrical stimulation of the skin through paired electrodes is perceived under the cathode.**

INTRODUCTION

It is well documented that electrical stimulation of the skin has rather specialized sensory effects which are likely due to direct excitation of the underlying afferent nerves [1]-[6]. However, the literature is not clear regarding where the electrically induced sensation is perceived. Repeated physiological experiments have demonstrated that when a nerve is placed on two-paired electrodes, it it depolarized under the cathode and is hyperpolarized under the anode [7], [8]. Because an action potential is generated at the depolarized site, such findings suggest that perceptible electrical pulses would be localized entirely or mainly under the cathode.

However, some behavioral and clinical studies have suggested that sensation for current can be perceived under the anode as well [9]-[12]. For example, comparing anodal and cathodal stimulation, Gibson found that anodal stimulation was less painful and less uncomfortable than cathodal stimulation at the same subjective intensity [9].

Furthermore, some physiological investigations have indicated that depolarization for cells or nerves may occur under the anode, as well as the cathode [13]-[16]. In particular, Ranck noted that when the cathode is placed on the skin surface over a nerve trunk, the nerve is depolarized beneath the cathode by current flowing from the anode to the cathode through the nerve; the region surrounding the cathode is hyperpolarized [13], [14]. The area of depolarization is generally smaller than that of hyperpolarization, while the magnitude of depolarization is stronger than that of hyperpolarization.

Ranck suggested that the relation of depolarization and hyperpolarization is reversed for anodal stimulation [13], [14]. In this case, a small area of hyperpolarization, with considerable magnitude, is generated beneath the anode and is surrouded by a larger area of depolarization with weak mangitude.

Action potentials, propagated along nerve fibers, are initiated by depolarization of the cell membrane. This, taken with the facts presented above, suggests that the threshold current at which an action potential occurs is lower for the cathode than for the anode. Reviewing the papers on electrical stimulation of the mammalian central nervous system, Ranck indicated that threshold current for the anode was 1.0 to 7.7 times as intense as that for the cathode [13]. Gibson reported that at threshold level, anodal stimulation to human skin required 1.3 to 2.0 times as much current as the cathode [9].

Localization at both detection and more intense levels has not been carefully studied, nor has the perceived magnitude of cathodal and anodal stimulation. The purpose of this paper is to examine perceived locus and intensity for electrical pulse stimuli delivered to the skin through paired electrodes. The cathode had the same size as the anode, so as to maintain a constant current density under each electrode. In Experiment 1, the observers were asked to report the electrode(s) under which a sensation was perceived for various conditions of electrode site, relative cathode and anode position, pulse number, and intensity level. Experiment 2 was an extension of Experiment 1. In addition to reporting the perceived locus for electrical pulse stimuli, the subjects judged the subjective intensity of whatever quality, touch, pressure, or pain that appeared under each electrode.

Three critical issues are examined in this paper. The first is the perceived locus for current pulses delivered

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through two-paired electrodes. In particular, we are concerned with whether or how perceived locus varies as current increases. A simple physiological hypothesis, based upon statements generally presented in textbooks, suggests that sensations would occur only at the cathode. For example, Thompson states, "when a nerve action potential is initiated, it will develop at the cathode" [17]. Grossman writes "if the membrane at the cathode is reduced to the threshold value for the cell, the action potential originates while the excitability is decreased at the anode" [18]. An alternative hypothesis, suggested by Ranck's model, is that electrical stimulation can be perceived not only under the cathode, but under the anode as well.

The second issue is to examine how perceived locus is affected by relative cathode-anode position, electrode site, and pulse characteristics. In reviewing physiological studies of electrical stimulation, Ranck notes, "there is surprisingly little data or theoretical consideration of the effects of stimulation of commonly used bipolar electrode configurations—side-by-side tips, staggered tips, and concentric electrodes. No doubt certain of these or other configurations could be used to advantage in certain cases, but it has just not been worked out" [14]. In Experiment 1 of this study, we used four electrode configurations, varying in distance, placement above common or different nerve trunks, and placement above identical or opposing arm surfaces.

The final issue is to describe how sensation magnitude for current grows under each of two-paired electrodes. In earlier studies, the subjects were usually asked to judge overall perceived intensity without regard to the possibility that the perceived intensity under one electrode may differ from that under the other. If, however, sensation is not limited to the cathode site, the perceived intensity may be different at the cathode and anode. In Experiment 2 of this study, the subjects were therefore asked to judge perceived intensity under each electrode.

EXPERIMENT 1

Method

Subjects: The subjects were the two authors and 19 undergraduates of the University of Western Ontario. After ethical approval of the study was obtained, volunteer subjects were solicited.

Apparatus: An isolated constant current stimulation system (Frederick Haer and Co. Pulsar 6) was used with Tektronix Series 160 waveform and pulse generators. This system provided electrical monophasic positive pulses to the subject's skin through two Grass silver electrodes of 8 mm diameter, which were filled with Cor-gel electrolyte gel.

Experimental Design: Four potentially effective variables were manipulated. The first was the site of the cathodal and anodal electrodes. Fig. 1 shows the location of electrodes on the left arm. Electrode *A* was placed over the ventral wrist in the region of the musculocutaneous nerve; electrode *B* over the ventral wrist to the right of electrode *A* with a center-to-center distance of 5 cm; electrode *C* over the ventral forearm with a center-to-center distance of 5 cm proximally from electrode *A*; electrode *D* over the dorsal wrist on the opposite side of electrode *A*; electrode *E* over the ventral forearm with a center-to-center distance of 17 cm proximally from electrode *A*. Electrodes *A*, *C*, and *E* ran along a straight line as shown in Fig. 1. Since electrode *A* was coupled with each of the other electrodes, there were four electrode pairs.

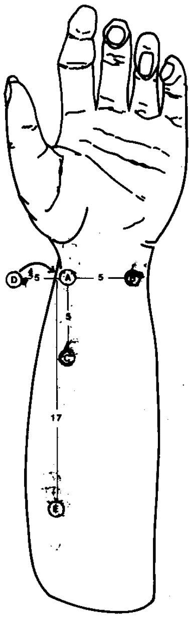

Fig. 1. Location of electrodes on the left forearm: the electrodes *A*, *B*, *C*, and *E* are placed on the ventral surface and electrode *D* is on the dorsal surface, opposite electrode *A*. The center-to-center distances from *A* to other electrodes are given in cm. The diameter of each electrode is 8 mm.

The second variable was the particular assignment of cathode and anode to each of the paired electrodes. When electrode *A* is paired with electrode *C*, either can be attached to the negative terminal of the constant current stimulation unit (with the other attached to the positive terminal). When *A* is the cathode, *C* is the anode and vice versa. Traditionally, in psychophysical research the proximal electrode *C* is assigned to be the cathode and the distal electrode *A* is assigned to be the anode, so that current flows proximally. However, careful study of the relative position of the two electrodes has not been undertaken.

When *A* is paired with *C* or *E*, the use of the terms "cathode distal" or "cathode proximal" is unambiguous. The former means that the cathode is at *A*; the latter means that the cathode is at the other site. This same convention will be used to refer to pairings of *A* with *B* and *D*: cathode distal means the cathode is at *A* and cathode proximal means the cathode is at *B* or *D*.

The third variable was single versus multiple pulses.

This variable was meaningful for two reasons. First, there is ample evidence (e.g., [3]) that single pulses and pulse trains have different psychophysical effects in terms of temporal summation, loudness growth, and threshold. Second, a lengthy pulse train applied to a distal cathode can create a series of depolarizations which pass a proximal site while the distal site is still being stimulated by later pulses in the train. For the single-pulse condition, a pulse of 1 ms duration was delivered; for the multiple-pulse condition, 40 successive pulses of 1 ms duration each were provided with a stimulus-onset-asynchrony of 10 ms, resulting in a train with a total duration of 391 ms.

The fourth variable was current intensity. Perceived localization, as a function of each of the first three variables, was studied at both weak, detection level and strong, pain threshold level.

Procedure: The subject was seated with the left hand resting on a table. Prior to the attachment of the electrodes, the subject's wrist and forearm were washed with an alcohol solution. Each of the five electrodes was then attached by a piece of surgical tape to the site indicated in Fig. 1.

Detection threshold and pain threshold were obtained by an ascending method of limits for each of 16 (four electrode sites × two relative polarities × two pulse characteristics) stimulus conditions. Current was increased in step sizes of about 0.08 ma; the intertrial interval was 2.5 s. Immediately after the subject reported 1) detecting an electrical pulse(s) or 2) reaching an intensity where the stimulus became painful, he was asked to indicate under which electrodes(s) the sensation or pain had occurred. The subject was allowed to choose either or both electrodes. To facilitate the locus judgments, the appropriate names *A*, *B*, *C*, *D*, and *E* were written on the tape covering each electrode. For the *A–B* combination, for example, the subject chose one from among the three alternatives of "*A*," "*B*," and "both."

The presentation order of electrode pairs and pulse characteristics was randomized for each subject. The presentation order of the cathode distal and cathode proximal conditions was also randomized.

Results

The sensation loci reported by the subjects were classified into three categories of "cathode," "anode," and "both," based upon the appropriate polarities. For the *A–B* combination in the cathode distal condition, for example, "*A*" responses were classified into the "cathode" category and "*B*" responses into the "anode" category. Since these responses were scored independently for detection level and pain level, the maximum possible frequency for a response category was 21 for each stimulus condition (one per subject).

Detection Level: For each response category, Fisher's exact probability tests were applied separately on four 2 (pulse) × 2 (polarity) tables, one for each site condition. For each response category, as well, Fisher's exact probability tests or chi-square tests were performed separately on two 2 (pulse) × 4 (site) tables, one for each polarity condition.[1] The results of these preliminary tests failed to show a significant result for any table, suggesting that the single versus multiple pulse condition was independent of the other two conditions. Consequently, the data for single and multiple pulse conditions were combined.

Table I shows the frequencies of each response category taken across the pulse conditions. If the subjects selected locus by pure guessing, the frequency for each response category would be an average score of 14 (42/3) for any combination of site and direction conditions. Since 21 subjects provided 42 observations (two per subject), the confidence limits were estimated on the basis of a binominal distribution with 21 independent trials [19]. The 95% confidence limits for 21 trials with $p = 1/3$ are 2.86 and 11.3; if the frequency is 23 or more in 42 observations, it is significantly higher than chance, whereas if it is six or less, it is significantly lower than chance. It is clear from the detection columns in Table I that responses designating "cathode" as the localized site were significantly more frequent than chance for six of the eight combinations of site and relative position conditions.

For each response category, Fisher's exact probability tests or chi-square tests were also performed on the 2 (polarity) × 4 (site) table derived from the detection data in Table I (in this case, three 2 × 4 tables were constructed, one for each response category).[1] These tests revealed the following significant results for the *A–E* combination: 1) the "cathode" response was more frequent for the cathode proximal condition than the cathode distal condition, $\chi^2(1) = 6.81$, $p < 0.001$; 2) the "anode" response was more frequent for the cathode distal condition than the cathode proximal condition, Fisher's test, $p < 0.001$; 3) the response of "both" was more frequent for the cathode distal condition than the cathode proximal condition, Fisher's test, $p < 0.05$. Other comparisons failed to yield significant differences as a function of relative polarity.

Pain Level: The same preliminary tests that were performed on the detection level data were applied to the data from the pain level. The results again showed that the pulse condition was independent of both site and relative position. As before, the data for single and multiple pulse conditions were combined.

The pain columns in Table I show frequencies of each response category taken across the single and multiple pulse conditions. It is clear that the "both" response was

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[1] Consider the two-way contingency table, in which the observed frequency is x_{ij} at the ith column and jth row ($i = 1, 2, \cdots, n$; $j = 1, 2, \cdots, m$; $N = n \times m$). This table is reducible to N 2 × 2 contingency tables:

$$\begin{bmatrix} x_{ij} & T_{i\cdot} - x_{ij} \\ T_{\cdot j} - x_{ij} & T - (T_{i\cdot} + T_{\cdot j} - x_{ij}) \end{bmatrix}$$

where $T_{i\cdot} = \Sigma_{j=1}^{m} x_{ij}$, $T_j = \Sigma_{i=1}^{n} x_{ij}$, and $T = \Sigma_{i=1}^{n} \Sigma_{j=1}^{m} x_{ij}$.

Each of the reduced tables was subject to a statistical analysis: for the tables containing frequencies of five or less, Fisher's exact probability tests were applied; for the other tables, chi-square tests were used.

TABLE I

FREQUENCIES OF "CATHODE," "ANODE," AND "BOTH" LOCALIZATIONS FOR ELECTRICAL PULSES AS A FUNCTION OF ELECTRODE SITE (*A* PAIRED WITH *B*, *C*, *D*, OR *E*), RELATIVE CATHODE POSITION, AND SENSATION LEVEL. $N = 42$

	Detection		Pain	
Localization	Cathode Distal	Cathode Proximal	Cathode Distal	Cathode Proximal
		(*A*–*B*)		
Cathode	38	35	17	10
Anode	3	6	1	2
Both	1	1	24	30
		(*A*–*C*)		
Cathode	27	21	14	7
Anode	11	17	2	6
Both	4	4	26	29
		(*A*–*D*)		
Cathode	33	32	16	4
Anode	5	9	0	1
Both	4	1	26	37
		(*A*–*E*)		
Cathode	20	40	3	20
Anode	13	1	0	0
Both	9	1	39	22

significantly more frequent than chance for seven of the eight combinations of site and relative position.

A 2 (polarity) × 4 (site) table was constructed for each response category from the pain data in Table I and was subject to a Fisher's exact probability test or a chi-square test (see footnote on preceding page). The significant results obtained from these tests were: 1) For the *A*–*D* combination, the "cathode" response was more frequent for the cathode at *A* than for the cathode at *D*, Fisher's test, $p < 0.001$; 2) for the *A*–*E* combination, the "cathode" response was more frequent for the cathode proximal condition than for the cathode distal condition, Fisher's test, $p < 0.001$; 3) for the *A*–*E* combination, the "both" response was more frequent for the cathode distal condition than for the cathode proximal condition, $\chi^2(1) = 7.02$, $p < 0.01$. The latter two results duplicate ones found at the detection level.

EXPERIMENT 2

The results obtained from Experiment 1 did not support the simple cathode hypothesis. Most strikingly, the sensation was generally perceived under the cathode at the detection level but was perceived under both electrodes at the pain level.

In an attempt to clarify further the relation between the perceived locus and sensation level for electrical stimulation, Experiment 2 was performed for nine current values ranging from 1.3 to 3.8 times the threshold current. These current values seemed to cover the dynamic range, defined as the ratio of the strongest to the weakest stimulus that the subjects report without reaching tolerance levels. The subject's task was to report the electrode(s) under which sensation was perceived and to judge the perceived intensity under the effective electrode(s) they reported.

Method

Subjects: The subjects were 16 undergraduates at the University of Osaka Prefecture. They were paid for participation.

Apparatus: An isolated constant current stimulator (Nihonkoden SEN-7103 and SS-102J) was used to provide single electrical monophasic positive pulses to the subject's skin through two Grass silver 8-mm-diameter electrodes, which were filled with keratin electrode paste. The pair of electrodes was constructed to fit into a plastic plate (1 cm wide × 20 cm long) with a center-to-center distance of 17 cm. A system comprising an Apple II microcomputer and a Sanwa time regulator determined the time schedule of warning buzzer, foreperiod, and intertrial interval. A trial sequence was started with a warning buzzer, followed by a 2 ms pulse to the electrodes after a foreperiod of 2.16, 3.47, or 4.81 s. The foreperiod was randomized for each trial. The intertrial interval was approximately 10 s. Further details of the apparatus are provided elsewhere [20].

Procedure: Each subject was seated with his/her right hand resting on a table. Prior to the attachment of the electrodes, the subject's right arm was washed with an alcohol solution. The plastic plate was strapped to the underside of the arm. One electrode was placed over the ventral wrist and the other was placed over the ventral forearm near the elbow. The electrodes were each in the region of the ulnar nerve and were separated by a center-to-center distance of 17 cm.

Each subject took part in two sessions that were separated by at least three days. For half the subjects in the first session, the wrist electrode was designated as the cathode and the elbow electrode as the anode. This condition is the same as the cathode distal condition in Experiment 1. For the remaining subjects, the polarity was reversed so that current flowed from the wrist electrode to the elbow electrode (the cathode proximal). For any subject, the polarity in the second session was opposite to that designated in the first session. The subjects were not informed of the relative electrode polarities.

In each session, an absolute threshold was first determined by a staircase procedure for a 2-ms single pulse. Subjects were asked to make about 30–60 yes/no judgments of whether current was present on the skin. If the current was detected, it would be decreased by a step (about 0.08 mA); if not, it would be increased by a step. The yes/no judgments for determining a threshold were stopped when the values of stimulus current reached an asymtotic level and hovered around this level. Immediately after the judgments were completed, the experimeter estimated the threshold current in accordance with standard computational procedures [21].

In the second part of each session, the experimenter determined the nine suprathreshold current values that were 1.3, 1.5, 1.7, 1.9, 2.2, 2.5, 2.8, 3.3, and 3.8 times as intense as the threshold current. Each of these stimuli was presented ten times, in randomized order, with the restriction that a block included nine different current values. The subject was asked to report the electrode(s) under which the sensation was perceived and to make verbal estimates of the perceived intensity. When the sensation was perceived under one electrode, the subject reported a single number; when the sensation was perceived under both electrodes, two numbers were reported, representing perceived intensity under each electrode. When no sensation occured under either electrode, the subject reported "nothing." The subjects were instructed that the ratio of the numbers used should reflect the ratio of the subjective intensities. No modulus or standard was employed.

Results

Perceived Locus: The subjects provided two types of responses-electrode(s) under which sensations occurred ("wrist," "elbow," or "both") and perceived intensity under the electrode(s). The responses about perceived locus were classified into four categories of "cathode," "anode," "both," and "nothing." In this experiment, the "cathode" category is applicable when sensation is perceived under the wrist electrode in the cathode distal condition or under the elbow electrode in the cathode proximal condition. Likewise, the "anode" category is suitable when sensation is perceived under the elbow electrode in the cathode distal condition or under the wrist electrode in the cathode proximal condition. The maximum possible score for each localization category was ten for each observer, reflecting the ten presentations of each combination of relative polarity and current level.

Fig. 2 shows the mean number of "cathode," "anode," and "both" responses taken across the 16 subjects as a function of current ratio (i.e., ratio of stimulus current to the threshold current), with the parameter of relative polarity. Fig. 2 excludes the results of the "nothing" responses, because they amounted to only 1.04% of the total responses and were not obtained for a stimulus ratio of 2.2 or greater. Given that, in essence, three categories were available, the average score obtained by random responding would be 3.3. The 95% confidence limits for 16 independent trials with $p = 1/3$ are depicted by two dotted horizontal lines in Fig. 2 (reflecting ten judgments per subject) where the upper limit is 5.8 and the lower limit is 1.1.

A two-way ANOVA for repeated measures was performed on the scores for each response category. For the "cathode" response, the main effects of polarity, $F(1, 15) = 5.36, p < 0.05$, and current, $F(8, 120) = 23.95, p < 0.001$, were significant, and the polarity x current interaction was significant, $F(8, 120) = 3.10, p < 0.001$. Taken together with Fig. 2, these results suggest that 1) "cathode" localization decreased with increasing current, 2) the cathode proximal condition generally produced "cathode" responses more frequently than the cathode distal condition, and 3) differences in the number of "cathode" responses between the proximal and distal conditions were greater at lower current values than at higher current values.

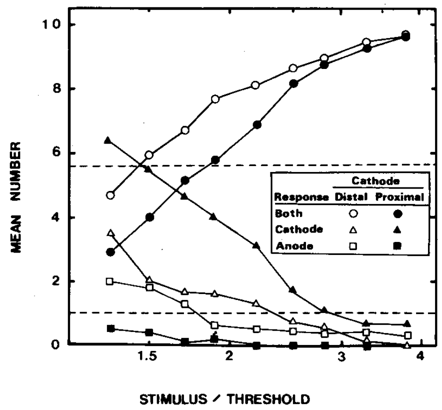

Fig. 2. Mean number of localization judgments in each response category as a function of ratio of current to the threshold, with the parameter of relative polarity. Results were obtained from 16 subjects. Open marks represent the cathode distal condition and filled marks represent the cathode proximal condition. Circles stand for the "both" localization; triangles for the "cathode" localization; squares for the "anode" localization. The dotted lines indicate the 95% confidence interval for chance performance.

For the "anode" response, the main effect of current was significant, $F(8, 120) = 4.21, p < 0.001$, suggesting that the "anode" localization decreased with increasing current. For the "both" response, the main effect of current was significant, $F(8, 120) = 27.47, p < 0.001$, reflecting an increase in dual localization with increasing current.

Perceived Intensity: To examine how perceived intensity for current varies as a function of relative polarity, electrode site, and current stimulus, we computed individual geometric means of the cathode sensation and the anode sensation magnitude estimates when subjects made localization judgments of "both" (and, therefore, provided two intensity judgments). Since one subject provided no "both" responses in one condition (she made only "cathode" responses when the cathode was proximal), her data were excluded in this analysis. Therefore, the results from 15 subjects were available. The single magnitude estimates for the "cathode only" and "anode only" responses were exluded because of the small sample sizes available as suggested in Fig. 2.

Fig. 3 shows the mean estimates for each of the "both" judgments as a function of current ratio, with relative polarity and electrode site as the parameters.

To identify how perceived intensity (Ψ) under each electrode grows as current ratio (ϕ/ϕ_0) increases, the power function $\Psi = k(\phi/\phi_0)^n$ was applied by the method of least squares to each of the magnitude estimates for the two loci. Separate power functions, one for perceived intensity under the cathode and the other for perceived in-

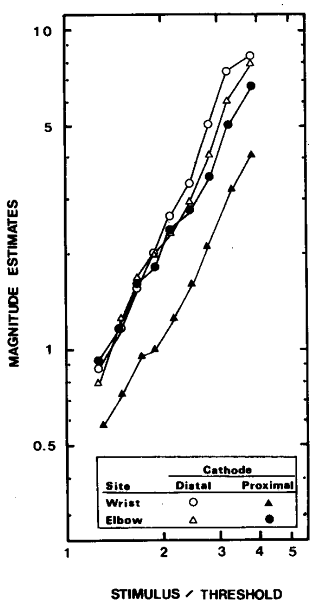

Fig. 3. Mean subjective intensity for each of the magnitude estimates given for dual localization as a function of current ratio. The parameters are electrode site and relative polarity: open circles, wrist electrode in the cathode distal condition; open triangles, elbow electrode in the cathode distal condition; filled triangles, wrist electrode in the cathode proximal condition; filled circles, elbow electrode in the cathode proximal condition. The circles represent the judgments for anode and the triangles represent the judgments for cathode.

TABLE II
MEAN SLOPE AND INTERCEPT OF THE POWER FUNCTIONS FITTED TO ANODAL AND CATHODAL MAGNITUDE ESTIMATES FOR "BOTH" RESPONSES AS A FUNCTION OF RELATIVE CATHODE POSITION AND ELECTRODE SITE. THE RESULTS WERE OBTAINED FROM 15 SUBJECTS

	Cathode Distal		Cathode Proximal	
	Wrist	Elbow	Wrist	Elbow
Slope				
M	1.98	2.06	1.79	1.58
SD	0.59	0.70	0.64	0.51
Intercept				
M	−0.17	−0.30	−0.46	−0.14
SD	0.56	0.46	0.50	0.47

tensity under the anode, were constructed for the wrist and the elbow.

Table II shows the mean slope (n) and intercept (log k) for each combination of relative polarity and electrode site. A two-way ANOVA performed on the slope data showed that the main effect of polarity was significant, $F(1, 14) = 4.7$, $p < 0.05$. This reflects the finding that the mean slope for the cathode distal condition (2.02) was steeper than that obtained when the cathode was proximal (1.68).

A similar two-way ANOVA performed on the intercept data showed that the main effects of polarity and site were not significant, but the polarity x site interaction was significant, $F(1, 14) = 5.63$, $p < 0.05$. The latter occurred because the intercept for the cathode at the wrist (−0.17) was larger than that for a paired anode at the elbow (−0.30), and, in the reverse condition, the intercept for the cathode at the elbow (−0.14) was larger than that for the anode at the wrist (−0.46). Consequently, the overall intercept for the cathode (−0.16) was larger than that for the anode (−0.38).

GENERAL DISCUSSION

The most striking finding obtained from Experiments 1 and 2 is that sensation is mainly perceived under the cathode at detection level, but, as current increases, it is more frequently localized under both electrodes.

Furthermore, when sensation for a particular current flow is perceived under both electrodes, the subjective intensity under the cathode is gnerally more intense than that under the anode. This is shown in Table II, where for either relative polarity, the intercepts, but not the slopes, are significantly different between the two electrodes. When the wrist electrode is the cathode, the mean intercept for that distal locus is larger than that for the elbow anode; for the reverse direction of current flow, the intercept for the wrist anode is smaller than that for the cathode at the elbow. The greater subjective magnitude, consequently, is associated with the cathode, no matter where it is sited on the arm, rather than the particular physical spot itself.

This result may parallel the observations of motor fibers by Berger, Gravenstein, and Munson [22] who, examining the effects of polarity on the twitch response of the thumb, showed that the maximal twitch was obtained when the cathode was close to the ulnar nerve at the wrist and the anode was elsewhere.

The findings obtained in this study run counter to the simple hypothesis that current is perceived exclusively under the cathode. They are, however, compatible with Ranck's model, which assumes that depolarization occurs under both cathode and anode, although to different degrees. If Ranck's assumptions are also valid for our paired electrodes, it may be predicted that 1) low stimulus current induces perceptible action current only under the cathode, but high stimulus current produces it under both electrodes, 2) the magnitude of depolarization is larger for the cathode than for the anode, and 3) if the magnitude of depolarization for a population of fibers is a determining factor of perceived intensity, the perceived intensity under the cathode is more intense than that under the anode.

Particular effects of relative polarity on perceived locus were found at the detection and pain levels for the A-E combination in Experiment 1. At both intensities, the electrocutaneous stimulus was localized more often at the cathode when that electrode was proximal. A similar result was obtained at both detection and moderate intensities in Experiment 2. These findings may possibly be accounted for in terms of collision block where the flow of the action current generated under the cathode is blocked or weakened by the flow of electrically generated antidromic current [23], [24]. For the cathode distal condition of the *A–E* combination, in which the cathode is near the wrist and the anode is near the elbow, the action current under electrode *A*, which is propagated through the ulnar nerve to electrode *E*, is likely to be weakened by the flow of stimulus current from electrode *E* to *A*. For the opposite condition of the *A–E* combination, where the cathode is more proximal than the anode, there may not be collision block, because the action current flows in the same direction as the stimulus current, i.e., from the distal to the proximal site.

The effects of relative polarity on perceived locus were not obtained for the *A–C* combination, however, even though this pair was also positioned along the musculocutaneous nerve. Since the major difference between the *A–C* pair and the *A–E* pair was the distance between electrodes, perception of the collision block may be more likely to occur as the separation of electrodes is widened.

The previously reported exponents (slopes) of the power function for electrical stimulation have varied considerably, from 0.7 to beyound 3.5 [25], [26], [27]. These differences have been ascribed to the effects of the correction of power function for threshold [28], to sensation level [20], [25], [26], [29], [30], and to regression and range effects [31]. Table II shows that the mean slope for a distal cathode (2.02) was steeper than that for a proximal cathode (1.69). This suggests a possibly new stimulus parameter influencing the exponent of the power function.

Our results are important not only in expanding the model of electrical stimulation, but in applying electrical stimulation to therapy for pain reflief and muscular rehabilitation. Previous clinical methods using electrical stimulation appear to have paid principal attention to the site of the cathode on the skin, because it has been believed that the electrical stimulation is perceived mainly at that location. These data suggest that the site of the anode deserves equal consideration.

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