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Effective Stimulation Distance for Current from Macroelectrodes

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Effective spread of stimulating current from macroelectrodes was measured using antidromic responses of axons of the pyramidal tract as an indicator of excitation. Both monopolar and concentric bipolar electrode configurations were tested with stimulating distances as large as 7mm. The effective stimulation distance was greater from monopolar electrodes especially at greater current strengths, but differences between the two configurations were frequently small and reversals of this trend occurred. There was no statistically significant difference between the estimates of effective stimulation distance made using large and small axons. The shape of current–distance curves was approximately parabolic using both bipolar and monopolar stimulation. A current strength of 0.5 to 1.0 mA will confine effective current from a monopolar electrode to a sphere of 2-mm radius, but will not stimulate all elements within that area. Even in a brain area as homogeneous as the pyramidal tract, there is still a great deal of variability from mean values in effective stimulation distance. Presumably, the variability would be even greater in more heterogeneous regions.

INTRODUCTION

Anyone who uses electrical stimulation to activate elements of the central nervous system eventually confronts the question of what elements are actually being stimulated. The question does not address the distance over which current spreads, but rather the distance over which the current activates neurons (15). Therefore, the investigation of this problem has taken the form of testing thresholds for excitation of various types of neural elements at known distances from a stimulating electrode. In this report, we will use the terms "effective stimulation distance" and "effective spread" to describe these measurements.

Abbreviations: PT—pyramidal tract, *D*—distance, *I*—current threshold.

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The terms microelectrode and macroelectrode have been applied to small and large electrodes, but we have found no clear definition of either type. In this paper, we will use these terms only in reference to metal electrodes and apply the term microelectrode to those with exposed surface areas less than 0.01 mm^2 and the term macroelectrode to those with areas greater than 0.2 mm^2. This definition covers the ranges used in studies of effective stimulation distance.

In spite of the widespread use of macroelectrodes in electrophysiology (11, 14, 22, 24), most research has concentrated on microelectrodes and distances shorter than 1 mm. The effective stimulation distance for microelectrodes is in the range from 1 mm/mA to 1 mm/0.4 mA, with the exact distance dependent on the electrical properties of the stimulated cells, the orientation of both the electrodes and the cells, the resistivity of the tissue containing the electrodes and the tissue containing the cells, the pattern of current flow as determined by tissue homogeneity and isotropy and electrode configuration, and the parameters of the current pulses (15). BeMent and Ranck (6) predicted that the diameter of the electrode tip would influence current density only when the distance to the site of stimulation is of the same order of magnitude as the diameter. Bagshaw and Evans (4) found that electrode diameter did influence effective stimulation distance *in vitro*, but even their coarse electrodes were small. Therefore, it is not clear that the effective stimulation distance for macroelectrodes will be the same as for microelectrodes.

It is often assumed that the effective stimulation distance for monopolar electrodes is greater than for bipolar electrodes, and in Bagshaw and Evans's (4) *in vitro* experiments, effective distances for concentric bipolar electrodes were smaller than for monopolar electrodes at distances greater than 1.25 mm from the stimulated element. No one has studied differences in effective stimulation distance for monopolar and bipolar electrodes *in vivo*, although this issue has been addressed theoretically (7, 20). In this study, we attempted to estimate the effective stimulation distance for macroelectrodes and to determine whether bipolar or monopolar stimulation confined stimulation more effectively. The medullary pyramid contains parallel axons that we stimulated with macroelectrodes to study effective stimulation over distances as great as 7 to 8 mm.

METHODS

Ten adult cats (2.53 to 3.75 kg) were anesthetized with 50 to 80 mg/kg α-chloralose i.p. and placed in a stereotaxic head holder. A small opening was produced in the cranium immediately to the right of the midline at P 13.5 and sealed with bone wax. The right postcruciate gyrus was exposed, and the dura was opened and replaced by a thin polyethylene film with a small hole

in it to permit penetration of a recording electrode to monitor the antidromic responses of stimulated neurons.

Body temperature was monitored by a rectal probe and maintained at 37.5°C by a DC servo-controlled heating pad. A bilateral pneumothorax was created and the animals were respired to maintain end-expiratory CO_2 concentration at 3.5 to 4.0%. Atelectasis was prevented by blocking the expiratory port of the respirator for two cycles every 5 min. Additional stabilization of the preparation for recording included suspension of the animal by clamps attached to a thoracic and a lumbar vertebral spinous process and drainage of the cerebrospinal fluid through the foramen magnum. Animals were paralyzed with gallamine triethiodide or decamethonium bromide.

A concentric bipolar electrode (Kopf, No. NE100; outer sleeve diameter 0.5 mm with 0.5 mm exposure; center pole 0.2 mm diameter, extending 1 mm beyond the outer sleeve, with 0.5 mm exposure) was placed stereotaxically in the right medullary pyramid (P 13.5, H -10, L 1). It was then adjusted vertically to the point at which the maximum corticofugal reflex discharge could be recorded upon stimulation of the contralateral forepaw. This electrode was used to stimulate the pyramid in either a bipolar (center pole cathodal) or monopolar (center terminal cathodal with the indifferent electrode placed in temporal muscle) fashion while searching for antidromically activated cells in the postcruciate forepaw focus. Although changes in the position of the indifferent electrode will change the pattern of current flow subtly, we chose not to investigate this variable in this study. The indifferent electrode was always placed in the same position, i.e., in temporal muscle immediately lateral to the stimulating electrode at P 13.5. Stimuli were 5-mA (supramaximal for the antidromically evoked cortical potential), 0.05-ms cathodal pulses, delivered at 2/s through a Tektronix 2620 constant-current stimulus isolator. This pulse-duration was used throughout these experiments—except in determining strength–duration curves—because it reduced both utilization time and interference of the stimulus artifact with detection of spikes with short latencies.

Recordings were made with glass microelectrodes, tip diameter 1 to 3 μm, 3 to 5 MΩ impedance, filled with 5% pontamine blue in 1.25 *M* sodium citrate. The signal was led from the electrodes into a Grass P15B preamplifier (half-amplitude filter settings: 30 Hz and 10 kHz) and displayed on Tektronix 565 and 5111 oscilloscopes.

Antidromic conduction of observed spikes was always verified by invariant latency at stimulation frequencies greater than 100/s and, frequently, by collision with an orthodromically conducted spike. When an antidromically activated pyramidal tract (PT) cell was isolated, the stimulus rate was reduced to 1/s and the threshold for antidromic activation was determined (taken as the current strength required to evoke a response to 50% of the stimuli). The

pyramidal electrode was then raised or lowered in its track in 0.5-mm increments and threshold determined at each site over a range of 6 to 8 mm or until the threshold exceeded maximum stimulator output (30 mA at 0.05-ms duration). The stimulation electrode was then changed to the alternate configuration, i.e., bipolar to monopolar or monopolar to bipolar, and the thresholds determined again for each site in the track.

For some axons the threshold determinations were repeated several times to check for effects of repeated movement of the electrode down the same electrode track. We anticipated shunting of current through a low-resistance fluid pathway created by repeated raising and lowering of the electrode (6). As reported, this does not seem to be a problem.

Strength–duration curves were determined for a number of axons using durations of 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, and 1000 μs. All threshold values for the strength–duration curves were determined at the electrode depth for which antidromic threshold was lowest.

At the conclusion of each experiment, positive current was passed through the pyramidal electrode at two or more sites in the track and the animal was perfused with normal saline followed by 5% potassium ferrocyanide in phosphate-buffered Formalin. The resulting Prussian blue reaction product permitted accurate histologic verification of electrode position in 50-μm frozen sections.

RESULTS

A total of 66 PT axons was studied. Monopolar stimulation was tested in 58 axons, bipolar stimulation was tested on 52 axons, and data for both monopolar and bipolar stimulation were obtained for 45 axons (7 axons were examined only for strength–duration curves). Minimum thresholds ranged from 0.04 to 5.56 mA, antidromic latencies ranged from 0.8 to 4.3 ms, and conduction velocities ranged from 10.9 to 58.4 m/s. Conduction velocities were computed using latencies of the antidromic responses (elicited at stimulus strengths well above threshold) over 46.7 mm, the estimated length of the axonal pathway from the pyramidal stimulation site to the cortical recording site (10).

Current Strength–Distance Relations. Data for all tested axons were normalized by calculating the effective stimulation distance as follows: in each electrode track, the site of minimum threshold (measured as I_{min}) for antidromic activation of a given axon was determined. This threshold was treated as an estimate of the minimum current required to bring the axon to threshold at the smallest distance from the electrode to the fiber. This distance (D_{min}) served as a reference point; under optimal conditions, D_{min} would be zero, meaning the electrode was in contact with the fiber. For each distance interval

(0.5 mm) the electrode was moved in its track from D_{min}, a new threshold was determined. The difference between the new threshold and the minimum threshold (measured as $I - I_{min}$) represented the current required for excitation over the distance from the new electrode site to the low-threshold site ($D - D_{min}$). Graphs depicting distance vs. current strength were drawn for all trials and evaluated by eye and statistically. Most statistical analyses, including computer curve-fitting of regression lines, were based on current strengths of 0.5, 1, 2, 3, and 5 mA.

Graphs of current strength–distance relationships (Fig. 1) were usually symmetric around D_{min}, but because the pyramids are bounded ventrally by fluid, we could trace only one-half of the curve completely. A selection of the varied pairs of curves obtained for monopolar and bipolar stimulation is illustrated in Fig. 1A–F, of which A and B are the most common. Occasionally, there were one or two sites within an electrode track where threshold decreased as the electrode was moved away from the fiber. The decreases generally occurred over a distance of 0.5 to 1mm, after which the threshold began to

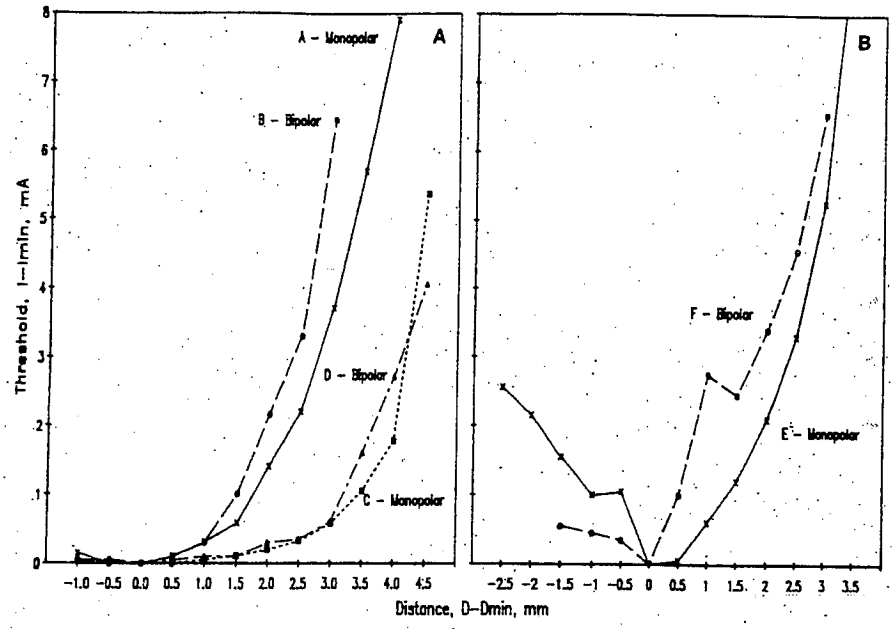

FIG. 1. Selected current strength–distance curves for pyramidal tract (PT) axons. Threshold stimulus strength is plotted on the ordinate as the deviation from the minimum threshold for that axon ($I - I_{min}$) and distance is plotted on the abscissa as distance from the point of minimum threshold ($D - D_{min}$). Both concentric bipolar and monopolar curves are shown for three different axons (A, B; C, D; and E, F). Pair A, B is the most commonly observed. Note the secondary minimum thresholds in E and F.

rise again at the same rate as prior to the threshold decrease (Fig. 1E and F). Other investigators have observed these threshold dips and have attributed them to the presence near the electrode track of axonal nodes, loops, or collaterals (3). Valverde's (23) reconstructions show many such collaterals or loops in PT axons in the region of the medullary pyramids in the rat. These probably also exist in the cat. Frequently, the thresholds for stimulating a given fiber stayed relatively constant deep within the electrode track, i.e., in and near the pyramid, possibly reflecting those sites at which the electrode had penetrated through the ventral aspect of the medulla or where the electrode track ran parallel to a fiber collateral for some distance.

The Nature of Effective Current Spread from Macroelectrodes. Comparison of curves fitted to data for individual axons revealed large variations in the slopes of the current strength–distance curves (compared by eye), reflecting a wide range of effective stimulation distances. Attempts to account for the differences between the tested axons in effective stimulation distances and the resulting differences in slopes of the strength–distance curves were made by evaluating the influence of differing distances of closest approach of the electrode to the fiber (reflected by different minimum thresholds) and the influence of conduction velocity (reflecting fibers of different diameter). A stimulus of given strength should activate a large-diameter fiber at a greater distance compared with a small-diameter fiber, yielding a greater estimate of effective current spread.

Minimum Distances and Current Strength–Distance Curves. For an electrode initially situated *lateral* to a fiber at some distance, D_0, greater than 0, movement of the electrode in its track by any distance, D_1, resulted in a new electrode-to-fiber distance, D_2, such that $D_2^2 = D_0^2 + D_1^2$ (Fig. 2 inset). Thus, when it is moved in its track, the actual change in distance of an electrode from a fiber, D_2, may be greater than the distance the electrode is moved, giving the appearance of smaller effective current spread. As the electrode is moved in its track farther from the fiber (greater distance D_1), this effect becomes less pronounced because D_0 becomes relatively insignificant. The resulting current strength–distance curve would be narrower near the minimum threshold point than would a curve for a track in which $D_0 = 0$, but at greater distances from the fiber, or at greater current strengths, the two curves should be similar. Therefore, estimates of maximum current spread should not be influenced by this effect of $D_0 > 0$.

To evaluate possible effects of differing distances of closest approach of the electrode to the fiber, i.e., differing D_0, on the shapes of current strength vs. distance curves, minimum thresholds were used as an indicator of the electrode's position closest to the fibers. Axons were parcelled into four minimum threshold groups (<0.4 mA, 0.41 to 1.0 mA, 1.01 to 2.0 mA, >2.01 mA) and average values for effective stimulation distance were determined at cur-

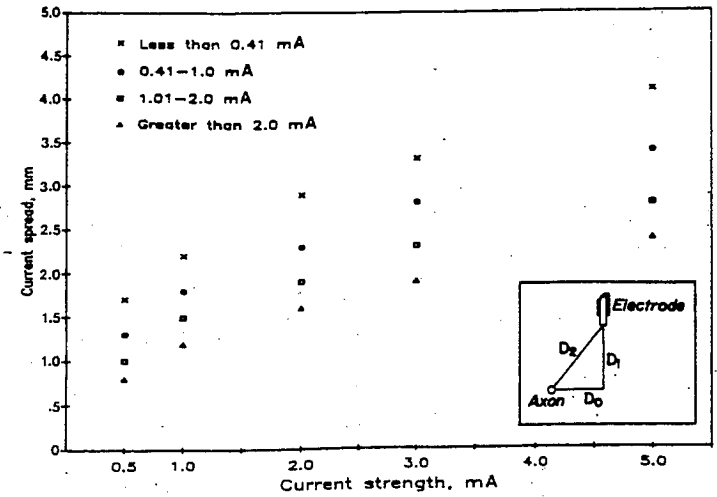

FIG. 2. Effective current spread from a monopolar stimulation electrode as a function of current strength and minimum threshold for exciting the fiber. The inset illustrates the relationship between distance along the electrode track (D_1) and distance from the axon (D_2) as discussed in the text.

rent strengths of 0.5, 1, 2, 3, and 5 mA for each group. Graphs of effective current spread vs. current strength (Fig. 2, for monopolar data) showed similar slopes for all groups, with curves offset from one another by approximately the differences in minimum thresholds. Axons with low minimum thresholds, i.e., small D_0, appeared to have strength–distance curves of slightly smaller slope than axons with high minimum thresholds, but the standard deviations of average values of effective current spread were large (0.8 to 1.7 mm). The effects of differing distances of closest approach should be most apparent at small current strengths (or short D_1 distances), but it was not possible to accurately compare slopes in this range because of variation in data. Similar results were seen for both monopolar and bipolar stimulation.

Because minimum threshold depends on fiber diameter as well as distance, additional curves were plotted for fibers of similar conduction velocities (greater than 35 m/s) so that differences in minimum threshold would reflect only differences in the distance of closest approach of the electrode to the fibers. There were no obvious differences between the slopes of these curves. It was also noted that of all axons of a given conduction velocity, the axon with the lowest minimum threshold could show the least or the greatest effective stimulation distance. These results indicate that the shape of a fiber's strength–distance curve does not depend to any great extent on the fiber's minimum threshold.

Conduction Velocity and Current Strength–Distance Curves. The influence of conduction velocity on the measured effective stimulation distance and the shape of current strength–distance curves is illustrated in Fig. 3. The graph plots data for axons parcelled into four velocity bins and depicts greater effective stimulation distances (and broader strength–distance curves) for rapidly conducting fibers compared with slowly conducting fibers. Examination of the values in Table 1, from which these curves were plotted, shows that although this tendency toward greater spread with greater conduction velocity was consistent, variability was great. Differences in effective stimulation distances shown in the graph were statistically significant ($P < 0.01$, Student's t test, at a current strength of 5 mA), at least between the fastest and slowest conducting fibers, but may be of little practical significance because of variability.

There was a positive correlation between the effective stimulation distance (measured at a current strength of 5 mA) and conduction velocity (Pearson's $r = 0.469$, Spearman's $\rho = 0.398$, Kendall's $\tau = 0.379$, $P < 0.004$, all for monopolar stimulation data). A slightly smaller correlation was found for bipolar stimulation data. In spite of the positive correlations, there were many instances in which there was less spread when tested with rapidly conducting fibers than with slowly conducting fibers. Thus, conduction velocity appeared to influence the shapes of current strength–distance curves, but some other factor may have been more important.

Mathematical Form of Current Strength–Distance Curves. Curves were fit to monopolar and bipolar data to determine whether or not effective stimulation distance could be described by a mathematical model. Linear, exponential, logarithmic, and power functions all described the data about equally well (correlation coefficients of $r = 0.588$ to 0.631) with the best estimate of effective stimulation distance on the basis of current strength (standard error of estimate of Y on X) being provided by a logarithmic function for bipolar data, $Y = A + B \cdot \ln(X)$, where $A = 1.432$ and $B = 0.754$, and a power function, $Y = A \cdot X^B$, for monopolar data, where $A = 1.494$ and $B = 0.462$ (X = current strength; Y = effective stimulation distance). The inverse square relationship (4, 7, 12), $k = I/D^2$, when expressed as a power function has an exponent of 0.5, very close to the 0.462 calculated for monopolar data and the 0.505 for bipolar data. Therefore, both curves are approximately parabolas. However, we noted that effective stimulation distance began to approach its maximum at a current strength of 2 mA and by 5 mA was at its maximum value for most axons. As the distance increased beyond 4 to 5 mm, the threshold current usually increased stepwise from a value less than 10 mA to a value greater than the maximum stimulator output (30 mA at 0.05 ms). The inverse square relationship predicts that threshold should continue to rise smoothly above 10 mA, but we seldom found thresholds of 10 to 30 mA.

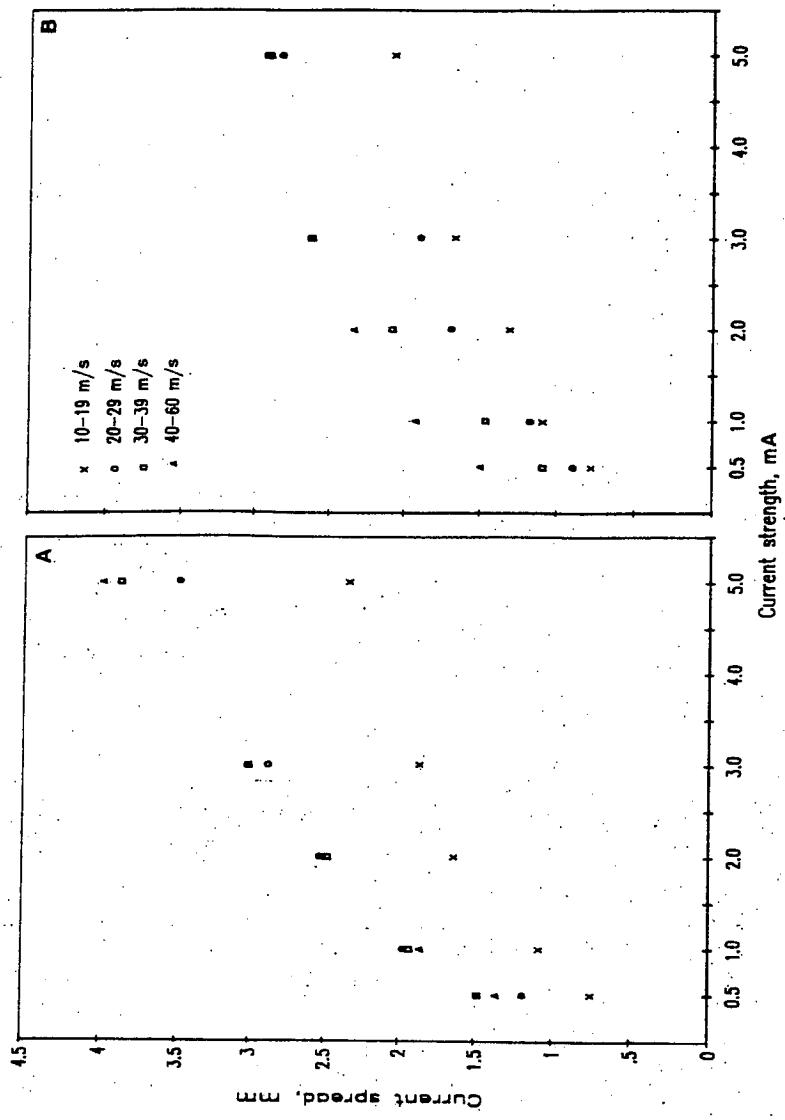

FIG. 3. Effective current spread from monopolar and concentric bipolar electrodes as a function of current strength and fiber conduction velocity. Fibers were parcelled into four bins of conduction velocity and effective current spread was plotted for strengths of 0.5, 1, 2, 3, and 5 mA.

TABLE 1

Effective Current Spread from Monopolar and Concentric Bipolar Electrode Configurations in Relation to Conduction Velocity

Conduction velocity (m/s)	Monopolar current strength (mA)				
	0.5	1	2	3	5
10–19	0.75 (0.23)[a]	1.08 (0.35)	1.64 (0.62)	1.87 (0.53)	2.35 (0.70)
20–29	1.18 (0.33)	1.97 (0.69)	2.53 (0.67)	2.88 (0.67)	3.49 (0.96)
30–39	1.48 (0.84)	1.93 (0.84)	2.48 (0.95)	3.01 (1.0)	3.88 (1.2)
>40	1.36 (0.66)	1.86 (0.77)	2.52 (1.0)	3.02 (1.3)	4.00 (2.0)
	Concentric bipolar current strength (mA)				
	0.5	1	2	3	5
10–19	0.78 (0.52)[a]	1.09 (0.60)	1.31 (0.67)	1.68 (0.58)	2.09 (0.66)
20–29	0.90 (0.57)	1.17 (0.64)	1.70 (0.99)	1.91 (1.1)	2.84 (0.87)
30–39	1.09 (0.74)	1.47 (0.81)	2.09 (0.87)	2.64 (1.2)	2.94 (1.1)
>40	1.50 (0.65)	1.93 (0.79)	2.35 (0.80)	2.63 (0.87)	2.92 (1.0)

[a] Mean in millimeters; standard deviation in parentheses.

Equipment failure does not explain this finding for we verified the stimulating current by measuring the voltage drop across a resistor in series with the preparation and the stimulus isolation unit. Beyond 5 to 6 mm, the stimulating current seemed to become ineffective for reasons we do not understand.

The positive *Y*-intercept values (seen in similar magnitude for the other three models), indicating current spread at a current strength of zero, suggested that although modeling can provide an approximation of effective stimulation distances, the regression equations were not highly descriptive of the data.

Strength–Duration Curves. Strength-duration curves are shown in Fig. 4 for five different PT axons. The curves in A were determined for bipolar stimulation, whereas those in B were determined for monopolar stimulation for the same five axons. For each axon, bipolar thresholds were higher than monopolar for every duration tested. Chronaxies measured for the three lower bipolar curves ranged from 80 to 100 μs for rheobases of 130 to 680 μA. It was not clear that the two upper curves had reached asymptotes even at durations of 1 ms, so no attempt was made to estimate either rheobase or chronaxie. For the same three fibers, the best estimates for monopolar chronaxies ranged from 75 to 115 μs for rheobases of 105 to 300 μA. These values for chronaxie of PT axons are similar to those for stimulation of axons elsewhere within the central nervous system [40 to 100 μs, (15)], but they are quite

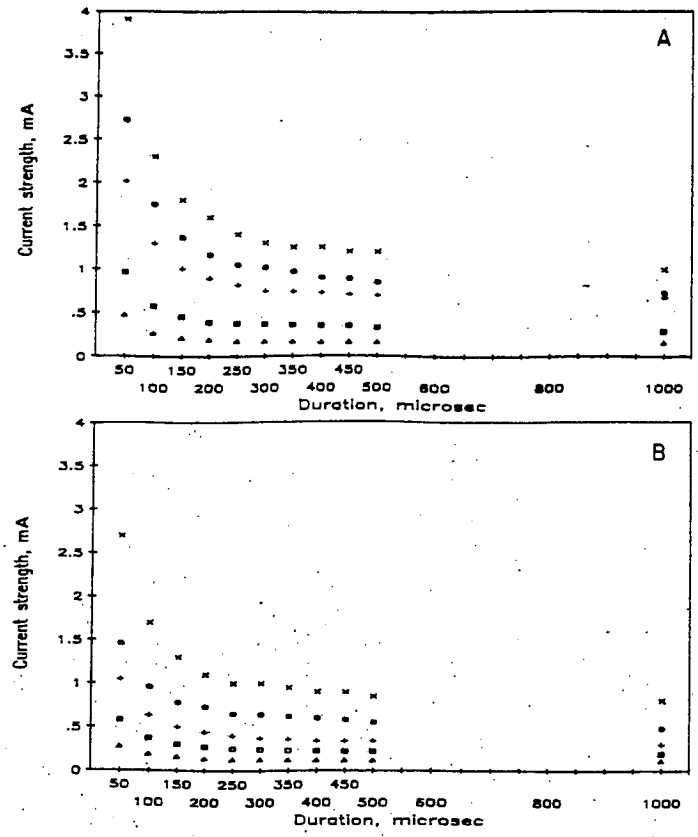

FIG. 4. Strength–duration curves for five PT axons determined for both concentric bipolar (A) and monopolar (B) stimulation.

different from those for microstimulation of single PT neurons within the cerebral cortex [100 to 450 μs, (21)].

Effects of Repeated Electrode Tracks. The effects of repeated electrode penetrations on the current strength–distance relationships were tested in seven axons (five tested with monopolar stimulation, two with bipolar stimulation) for as many as four repeat trials. In all cases, repeat threshold determinations were nearly identical, including the first trials in a given animal. In one instance, the low-threshold point in the electrode track shifted superficially 0.5 mm on one repeat testing, but the slope of the strength–distance curve was unchanged. Furthermore, comparison of the average effective stimulation distance at current strengths of 0.5, 1, 2, 3, and 5 mA for the first and last tracks in each animal (all tested with monopolar stimulation) yielded less than 10% variation.

Monopolar vs. Bipolar Stimulation. Table 2 shows average effective stimulation distances for stimulus strengths of 0.5, 1, 2, 3, and 5 mA for 38 axons from which paired monopolar and bipolar stimulation data were obtained. Average monopolar and bipolar values for these 38 axons did not differ from average values obtained from evaluation of all axons tested with monopolar stimulation (51 axons) or bipolar stimulation (45 axons) alone. Effective stimulation distance for a monopolar electrode was greater than from a bipolar electrode at all current strengths, with the greatest (statistically significant) differences at high current strengths. In view of the large standard deviations, however, effective current spread from the two electrode configurations should be considered similar.

Figure 5, a scatter plot of effective stimulation distances for both monopolar and bipolar stimulation, illustrates the amount of variation and may present a more accurate representation than average values. At a stimulus strength of 5 mA, current can be effective over 1 mm to 7 mm from a monopolar electrode or over 0.8 mm to 4.8 mm from a bipolar electrode. Similarly wide ranges were present at other stimulus strengths, but both the upper and lower limits of the ranges were slightly smaller in magnitude.

Effective stimulation distances at current strengths of 0.5, 1, 2, and 3 mA were greater for monopolar stimulation than for bipolar stimulation in 21 of the 38 axons for which both monopolar and bipolar stimulation data were obtained. For 10 of the 38 axons, effective distances were greater with bipolar stimulation at most current strengths. The proportion of axons for which monopolar distances were greater than bipolar distances increased with in-

TABLE 2

Comparison of Effective Stimulation Distance Values for Monopolar and Concentric Bipolar Stimulation from Axons Tested with Both[a]

	Current strength (mA)				
	0.5	1	2	3	5
Monopolar	1.17 (0.65)[b]	1.68 (0.82)	2.21 (0.94)	2.66 (0.36)	3.23 (0.46)[c]
Bipolar	0.99 (0.64)	1.32 (0.74)	1.82 (0.87)	2.26 (0.42)	2.92 (0.60)
Significance[d]	n.s.	n.s.	$P < 0.02$	$P < 0.02$	n.s.[c]

[a] Values are similar when data for all monopolar (51 axons) and all bipolar (45 axons) trials are evaluated.

[b] Mean in millimeters; standard deviation in parentheses.

[c] Four axons had such broad strength–distance curves that 5-mA values could not be determined. The average effective spread at 5 mA was greater than indicated. Median value for monopolar stimulation at 5 mA was approximately 3.4 mm.

[d] Significance tested by Student's t test for paired data.

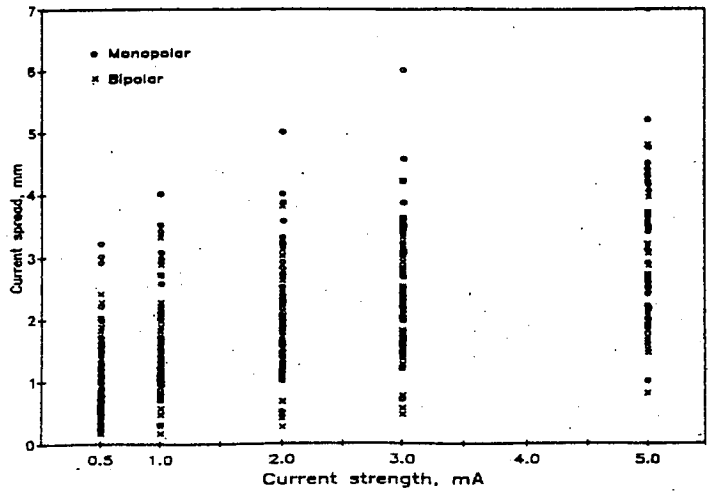

FIG. 5. Scatter plot of the effective current spread from monopolar and concentric bipolar stimulation electrodes as a function of current strength. Data are shown for 38 axons from which both monopolar and bipolar data were obtained.

creasing stimulus strengths, with a concurrent decrease in the number of axons that showed equal distances from monopolar and bipolar electrodes. Eighteen of the 38 axons had wider current strength–distance curves (reflecting greater current spread) with monopolar stimulation, 15 axons had equal curves, and 5 had wider curves with bipolar stimulation. Even when there were consistent differences between effective stimulation distances for monopolar and bipolar stimulation, the differences were small.

Electrode Configuration and Minimum Threshold. The minimum threshold (I_{min}) of a fiber was not associated with the likelihood that there would be greater effective stimulation distances for one electrode configuration. Minimum thresholds for monopolar and bipolar stimulation were often not the same in a given axon, but the existence of a difference in minimum threshold at D_{min} was also unrelated to the relative magnitude of monopolar vs. bipolar effective stimulation distances. When effective distances were greater with monopolar stimulation, 56% of the axons had lower thresholds for monopolar than for bipolar stimulation, 11% had the same thresholds for both electrode configurations, and 33% had lower thresholds for bipolar stimulation. Similar results were seen when there were greater effective distances for bipolar than for monopolar stimulation.

Electrode Configuration and Conduction Velocity. When evaluated with respect to conduction velocity, the differences between estimates of effective stimulation distances for monopolar and bipolar electrodes became more

distinct. Table 1 (values graphed in Fig. 3) shows the relationship between fiber conduction velocity and the effective stimulation distance. Values for monopolar and bipolar electrodes were similar at low current strengths, but estimates of effective distances for monopolar electrodes were greater than those for bipolar electrodes for all conduction velocities at current strengths greater than 1 mA. The differences were minimal for slowly conducting fibers and relatively large for rapidly conducting fibers. However, because of large variability the differences were neither practically nor statistically significant (Student's t test for paired data).

DISCUSSION

Our attempts to characterize effective stimulation distance were limited by large and frequent deviations of distances of effective spread from average values, and it is likely that the efforts of other investigators were also hindered by variability. Consequently, both estimates of effective stimulation distance and models from which they may be made must be used cautiously because these are often based on average values. The average values reported here provide at least an approximation of the effective stimulation distance from a macroelectrode in the central nervous system over a wide range of current strengths. Use of average values together with consideration of standard deviations can permit application of these values to specific situations. For instance, to confine a monopolar stimulus (with parameters comparable to those used in this study) to within a 2-mm radius of the electrode, a stimulus strength of 0.5 to 1.0 mA would be appropriate (at least when stimulating fiber tracts). This would restrict the stimulus to a small area but would not activate all elements within the area. To stimulate all fibers within a 2-mm radius of the electrode, a stimulus strength of 3 to 5 mA would be needed.

There are few previous reports of current spread from macroelectrodes with which to compare our results. All the applicable studies have dealt only with monopolar stimulation. The data in Ranck's (15) review represent current strength–distance data which have been normalized to a 200-μs pulse. Using these values and the strength–duration curve of BeMent and Ranck (5) to compensate for our 50-μs pulses results in about a 50% reduction in our current strengths. Our own strength–duration curves (Fig. 4) also indicate that threshold current strength is reduced by 50% when pulse duration is increased from 50 to μs to 200 μs. This brings our estimates of effective stimulation distance into agreement with those summarized by Ranck (15). Use of surface stimulation should double the amount of current flowing in the tissue compared with the amount that would have been present from deep stimulation in our study with the same strength and duration. Consequently, BeMent and Ranck's (5) value for effective spread of a current of 0.25 mA (approximately 1.1 mm, estimated from their Fig. 4) for surface stimulation

of cat's dorsal columns is similar to the effective spread of a 0.5-mA pulse (1.17 mm) in our study.

Only Akaike *et al.* (1), who studied the rabbit vestibulospinal tract, evaluated current spread over distances comparable to ours. Using a 0.2-mm diameter electrode and 100-μs pulses, they found an effective spread of 2 to 3 mm at 1 mA. Correction for pulse duration results in approximately 30% reduction in thresholds such that a 1-mA stimulus of 100-μs duration would have spread effectively only about 2 mm in our study. The amount of current required to stimulate a fiber 2 to 3 mm from our electrode would be 2 to 3 mA compared with 1 mA obtained by Akaike *et al.* (1).

The smaller effective stimulation distance in our study compared with that of Akaike *et al.* (1) may be attributed to several factors. The excitabilities of fibers in the cat pyramidal tract may be different from those of the rabbit vestibulospinal tract. The conduction velocities of axons in the rabbit vestibulospinal tract are greater than for the cat pyramidal tract. Estimates of current spread are greater for faster conducting fibers, at least with larger currents. The impedance of the rabbit vestibulospinal tract may be less than that for the cat pyramidal tract, although there is no reason to believe that any difference would be of significant magnitude. Furthermore, the spread of current may differ because of differences in the areas of the exposed electrode tips used in the two studies, with the effective stimulation distance for a given current less for large electrodes than for small ones (4, 7). Assuming that the electrodes used by Akaike *et al.* (1) had a conical tip exposed for 0.5 mm, the exposed area would be 0.16 mm^2. In contrast, the area of the Kopf electrode is 0.34 mm^2. The greater tip exposure of the Kopf electrode may result in less effective current spread. The rheobases we measured for monopolar stimulation were 10- to 20-fold greater than those reported by BeMent and Ranck (5) using 100-μm wires with an exposed area of 0.008 mm^2, giving support to the idea that current spreads less from larger electrodes. Each of the above factors probably plays a role in altering effective current spread.

No previous study has provided *in vivo* data regarding the relative effective stimulation distances for monopolar and bipolar electrodes. Our data indicate that the same current is effective slightly farther from a monopolar electrode than from a concentric bipolar electrode. The difference in effective spread becomes greater at large current strengths. This is consistent with the findings of Bagshaw and Evans (4) and Comte's (7) mathematical model, except that they show that current is effective farther from a bipolar electrode than from a monopolar electrode at small current strengths. Practically, the differences in effective spread from the two electrode configurations are small and are made less significant by the relatively large variation. We did not test side-by-side bipolar electrodes, which might behave differently from concentric ones (4).

The variation in effective stimulation distance among axons in this study is reflected in graphs of current strength–distance relationships as curves of differing slopes. It is apparent in these graphs that effective current spread is much greater when measured for certain axons than for others (i.e., the curve is broad). Curves with comparable variations in slopes are seen in both micro- and macrostimulation studies of other investigators. These variations have been attributed to inherent differences in excitabilities of the neural elements, e.g., as a result of different fiber diameters (5, 8, 9, 12, 18); differences in local tissue properties (5, 6, 9, 16, 17, 19) or, for fibers, differing nodal geometries (18); variations in the actual distance of the stimulation electrode from the activated element (3, 6); and to differences in the states of the test animals (2, 25).

Variations in the slopes of current strength–distance curves probably do not result from differences in how close the electrode is to the fiber at its closest approach. Such an influence would be most apparent at small stimulus strengths and short distances; we often found larger differences in slopes at large current strengths. These differences in slope are partially explained by differing fiber excitabilities. Fibers with greater conduction velocities and larger diameters were associated with broad parabolic current strength–distance curves in contrast to the narrow parabolic curves of slowly conducting fibers. However, other effects also determine the extent of effective current spread because the axons with lowest minimum thresholds and greatest conduction velocities were not always associated with greatest effective current spread.

The pyramidal tract is likely to be electrically anisotropic as suggested by Ranck and BeMent (17) for areas in which fibers run predominantly in one direction. With the wide range of axon diameters within the pyramid, it is probably also heterogeneous (13) with different radii having different conductivities. This may create local current pathways of different conductivities and perhaps contribute to differences in current strength–distance curves.

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