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Protective Effects of Patterned Electrical Stimulation on the Deafened Auditory System

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ABSTRACT

Multi-unit recording and mapping techniques have been applied extensively in normal hearing cats to map the representation of acoustic signals. Our previous studies (Snyder et al., 1990, 1991, 1994) have shown that these techniques can be adapted to map the representation of electrical signals in deaf cats. The signals were delivered using an intracochlear electrode that has been developed and previously described under previous contracts (Rebscher et al., QPR#9; Contract N01-DC-4-2143). This Progress Report summarizes studies of the effects of phase duration on threshold and spatial distribution of neuron responses in the inferior colliculus of deaf adult cats to intracochlear electrical stimulation.

This study includes data from 29 adult cats that were deafened either by co-administration of kanamycin and ethacrynic acid or by neonatal administration of neomycin. Adult deafened cats were implanted with an intracochlear stimulating electrode 1-2 weeks after deafening. Neonatally deafened cats were implanted 6-8 weeks after deafening. Intracochlear electrodes consisted of a silastic carrier with 4 to 10 Platinum-Iridium wires ending in 200 μ ball contacts. The contacts were usually arranged in bipolar pairs oriented in radial or off radial configurations. Stimuli were delivered as charge balanced biphasic pulses or charge balanced sinusoids. Extracellular recording microelectrodes were inserted into the inferior colliculus (IC) using a standardized trajectory to penetrate across the frequency representation of the IC. At intervals of 100 μm measurements of threshold were taken to stimulus wave forms applied to intracochlear electrodes.

In a total of 67 penetrations through the IC of 29 cats spatial tuning curves (STCs) were constructed simultaneously for 0.2 ms/phase pulses and 5 ms/phase (100 Hz) sinusoids. The minimum threshold and STC width were measured in each of these STCs.

These results suggest that changing the phase duration of a stimulus wave form for intracochlear electrical stimulation alters many properties of auditory nerve (AN) activation including threshold, dynamic range and spread of activation across the auditory nerve array. As expected from the well understood properties of electrical activation of neurons, shorter phase duration signals have higher thresholds than longer phase duration signals, i.e., they require higher peak current (more charge/phase) to activate nerve fibers. Using biphasic pulsatile stimuli which vary systematically from 0.2 to 5 ms/phase, strength (to threshold) vs. duration curves were constructed and four estimates of chronaxie were obtained. These four estimates of chronaxie are consistent with activation of AN neurons at their cell bodies or at their unmyelinated processes and are inconsistent with activation at their myelinated axons. However, contrary to expectations, estimates of the intracochlear spread of activation and dynamic range of activation were also systematically affected by phase duration. Shorter phase duration stimuli spread more rapidly across the AN array and saturated the array more rapidly than longer phase duration signals. These result suggest that short phase duration stimuli might have certain disadvantages as carriers for signals used in CI speech processing strategies. The implications for cochlear prosthesis are discussed.

STIMULUS WAVEFORM FACTORS INFLUENCING PHYSIOLOGICAL THRESHOLD AND SPATIAL SELECTIVITY IN INFERIOR COLLICULUS NEURONS TO INTRACOCHLEAR ELECTRICAL STIMULATION.

INTRODUCTION

Initial cochlear prostheses were single channel devices, that transduced acoustic signals into an electrical signal delivered to a single contact within the cochlea (see Schindler and Merzenich, 1983 for review). However, over the course of the last two decades, the necessity for distributing the speech signal among multiple stimulus channels in cochlear implants has been widely accepted. In order to achieve this distribution, the speech signal must be divided into frequency bands; these separate bands of information must be delivered to different electrode channels; and each electrode channel must activate a different (and presumably appropriate) information channel in the auditory nervous system. In an attempt to accomplish this goal, several speech processing strategies have been devised. These processing strategies include: 1) Compressed analogue processing (CA). In this strategy the speech signal is divided into a number of frequency bands, the amplitude range of each acoustic band is compressed into the dynamic range of electrical hearing, and each compressed signal is then delivered to a different intracochlear contract. 2) Amplitude modulation processing of pulse trains (CIS, SPEAK, MPEAK). In these strategies, speech is also divided into frequency bands, the envelope of each band is extracted and that envelope is used to modulate the amplitude of a pulse train carrier, each modulated carrier is delivered to an "appropriate" intracochlear electrode. 3) Combination processing (ACE). In this process, both analogue and pulsatile processing are employed. Thus these three processing strategies employ dramatically different stimulus parameters. Among these parameters are stimulus wave form (sinusoids in CA vs. pulses in CIS and SPEAK), stimulus phase duration (10s of ms in CA to 10s of μsec in CIS) and stimulus repetition rate (e.g., 250 pps/channel in SPEAK and up to 3000 pps/channel in CIS). In addition, these strategies divide the speech signal into different numbers of frequency bands and deliver these bands to different numbers of electrodes. The electrodes in turn are positioned at different locations along the cochlear spiral and may be arranged in different configurations including rings (Nucleus) and off-radial balls (Clarion).

In the physiological studies of intracochlear electrical stimulation (ICES) conducted in our laboratory (Snyder et al., 1990, 1991, 1995, 1998, Leake et al., 1995; Beitel et al., 1993, 1995, 1998), we have found that many of these, as well as other, variables influence physiological responses of the auditory system to ICES. They determine, in part, such important parameters as threshold, dynamic range, spatial spread (channel interaction) and relative activation location. In order to quantify the effects of some of these stimulus parameters, we have conducted experiments using different stimulus wave forms to map responses across the cochleotopic organization of the auditory midbrain of deafened adult cats. These response maps have been used to construct spatial tuning curves (STCs) which provide an estimate of minimum threshold, dynamic range and spatial tuning of electrical signals (spatial spread of excitation across the auditory array) in deaf animals (see Merzenich and White, 1977; Snyder, et al, 1990, 1991; Montney et al., 1998). This report will summarize our results using stimulus wave forms that differ in shape (sinusoids vs. pulses), in phase duration (0.2 to 5 ms/ phase) and in repetition rate (1-2 pps to 1000 pps)

METHODS

Deafening: The effects of signal wave form and phase duration were examined in 29 adult cats. Twelve of these cats were prior-normal adults which were deafened using subcutaneous injections of kanamycin and amino-oxyacetic acid as described by Leake et al., (1987), or co-administration of kanamycin and ethacrynic acid as described by Xu et al. (1993). Animals were first sedated with an IM injection of ketamine and acepromazine and an intravenous catheter was inserted. A baseline auditory brainstem response (ABR) intensity series was recorded and threshold determined visually. kanamycin (300 mg/kg) was injected subcutaneously and ethacrynic acid was infused intravenously (1 mg/min) until no ABR responses were obtained to clicks at equipment intensity limits (110 dB peak SPL). ABRs were monitored for at least 4 hours to ensure that hearing did not recover.

Seventeen cats were deafened as neonates using intramuscular injections of neomycin (50 mg/day for 16 days) using procedures described by Snyder et al., (1990). The time course and completeness of their hearing loss was documented using the auditory brain stem response (ABR) to clicks and the frequency following response (FFR) to 500 Hz tones. These animals were allowed to survive a minimum of 6 months before acute physiological experiments were conducted.

Implantation: Animals were implanted using sterile surgical technique approximately two to 6 weeks after deafening. A surgical level of anesthesia was induced using Nembutal and the left auditory bulla was opened to access the round window. The round window membrane was opened and the intracochlear electrode inserted into the scala tympani. The electrode was held in place with Histocryl™ tissue adhesive applied to a dacron cuff at the round window. We have employed an intracochlear electrode designed and manufactured by in our lab. It consists of a silicone elastomer carrier with up to 10, but usually less, platinum-iridium wires ending in ball shaped contacts (see 9th Quarterly Progress Report, Oct. 1, 1996-Dec. 31, 1996, Contract #N01-DC-4-2143, figure 1). The contacts consist of two pairs of wires each wire ending as a ball contact. The paired contacts are arranged as an apical pair and a basal pair separated by 2 mm. Each contact in pair is separated from the other by 1 mm and the pair is arranged in an off-radial orientation. The contact at the apical tip of the electrode is labeled as #1 and successively basal contacts are labeled 2, 3 and 4. Stimulation using different combinations of these contacts activated either as bipoles or as monopoles (i.e., employing a silver wire in the scalp as a return) has allowed us to test the effects of contact placement both around the carrier and relative to the anatomical structures within the cochlea. At least two weeks of post implant recovery time was allowed so that the animals could recover from the surgery prior to the terminal physiological experiment.

Acute Physiological Recording: The procedures for recording and mapping multi-unit responses to intracochlear electrical stimulation have been described in detail in our previous publications (Snyder et al., 1990, 1991, 1995). In brief, tungsten microelectrodes were introduced along a standardized penetration trajectory into the IC at right angles to its isofrequency representations. Thus a single penetration traverses most or all the cochleotopic organization of the IC and allows systematic sampling of responses across a wide range of frequencies. In the course of each penetration multi- and single unit responses were recorded and neural thresholds determined at sequential locations separated by 100 micron intervals. At each location responses to multiple stimulus wave forms were recorded and thresholds to each determined using bipolar stimulation. After a penetration has been completed, the threshold stimulus level in the IC central nucleus (ICC) is plotted as a function of penetration depth. Since these plots of threshold vs. depth for one stimulus condition have a "V" shape in the ICC, we have called them spatial tuning curve (STCs). These STCs can be used to infer the effects of various stimulation parameters on minimum threshold, dynamic range and spread of excitation across the auditory nerve.

RESULTS

There are number of ways that STCs can be characterized. Figure 1 illustrates some of these measures. Each curve has a minimum threshold which occurs at a specific best location within the ICC. In previous publications we have demonstrated that minimum STC threshold varies among animals and correlates with other measures of stimulus threshold including behavioral threshold, minimum neural threshold in primary auditory cortex (AI) and EABR threshold (see Snyder et al., 1990, 1991, Leake et al., 1992, 1995; Beitel et al., 1993, 1994, 1995; 1998). Best location varies systematically with the intracochlear location of the contacts that are excited. The best locations of STCs evoked by stimulation of more apical electrode pairs are located more superficially in the IC, whereas STC evoked by more basal electrodes are located deeper in the IC. In addition to minimum threshold and best location, each STC also has a characteristic width. We have chosen to measure that width at a standard level of 6 dB above threshold (i.e., twice minimum threshold current). In previous publications we have shown that STC width is

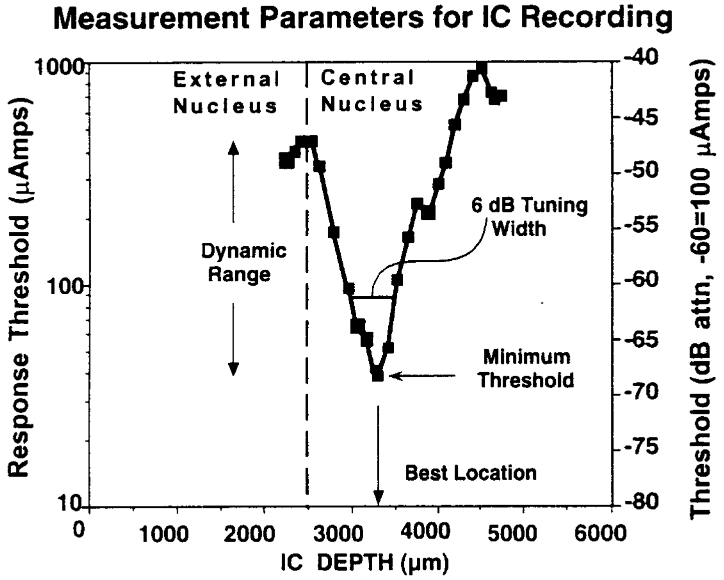

FIGURE 1. Definitions of measurement parameters used to characterize IC spatial tuning curves (STCs). Minimum threshold (in μAmps peak-to-peak) is the lowest stimulus level that evokes a response in the central nucleus of the IC (ICC). 6 dB width is the width in millimeters at 6 dB above minimum threshold. Dynamic range is the range of stimulus intensities that evoke responses limited to the ICC. Best location is the depth at which a minimum threshold stimulus evokes a response.

correlated with the extent of the spread of excitation that is produced across the auditory nerve array by stimulus spread along the cochlear spiral (Snyder, 1990, 1991). Finally, each curve has a dynamic range, which is defined as the range of intensities over which a stimulus evokes a response while retaining at least some spatial selectivity, i.e., does not excite neurons across the external and central nuclei simultaneously. Using these measures, we can compare STCs generated by different stimulus wave forms (e.g., sinusoids vs. pulses), different stimulus phase duration (e.g., biphasic pulses with 0.2 ms/phase vs. pulses of 5 ms/phase) and different electrode configurations (e.g., bipolar vs. monopolar) in animals with different auditory experience (neonatally deafened vs. prior normal adults).

Stimulus wave form is the first stimulus parameter that might be expected to influence excitation threshold and intracochlear spread. In order to determine the effect of stimulus wave form, we compared the STC widths and thresholds determined for pulses vs. sinusoids in individual penetrations through the IC. In these experiments both these wave forms had the same phase duration (5 ms/phase) and were delivered at the same repetition rate (3/sec). The resulting STC measures for these two signals in two cats are illustrated in Figure 2. In Figure 2a, the STCs evoked by activation of electrode pair 1,2 using a 100 Hz sine wave and a 5 ms/phase biphasic pulse are nearly identical. Their minimum thresholds are comparable (20 μAmps or for the pulse vs. 22 μAmps for the sinusoid) and their 6 dB widths and dynamic ranges are indistinguishable at 1.3 mm and 20 dB respectively. In Figure 2b the STCs have significantly different, but comparable, minimum thresholds (22 μAmps for the pulse and 40 μAmps for the sinusoid), comparable 6dB widths (0.60 mm for the pulse and 0.74 mm for the sinusoid) and nearly identical dynamic ranges

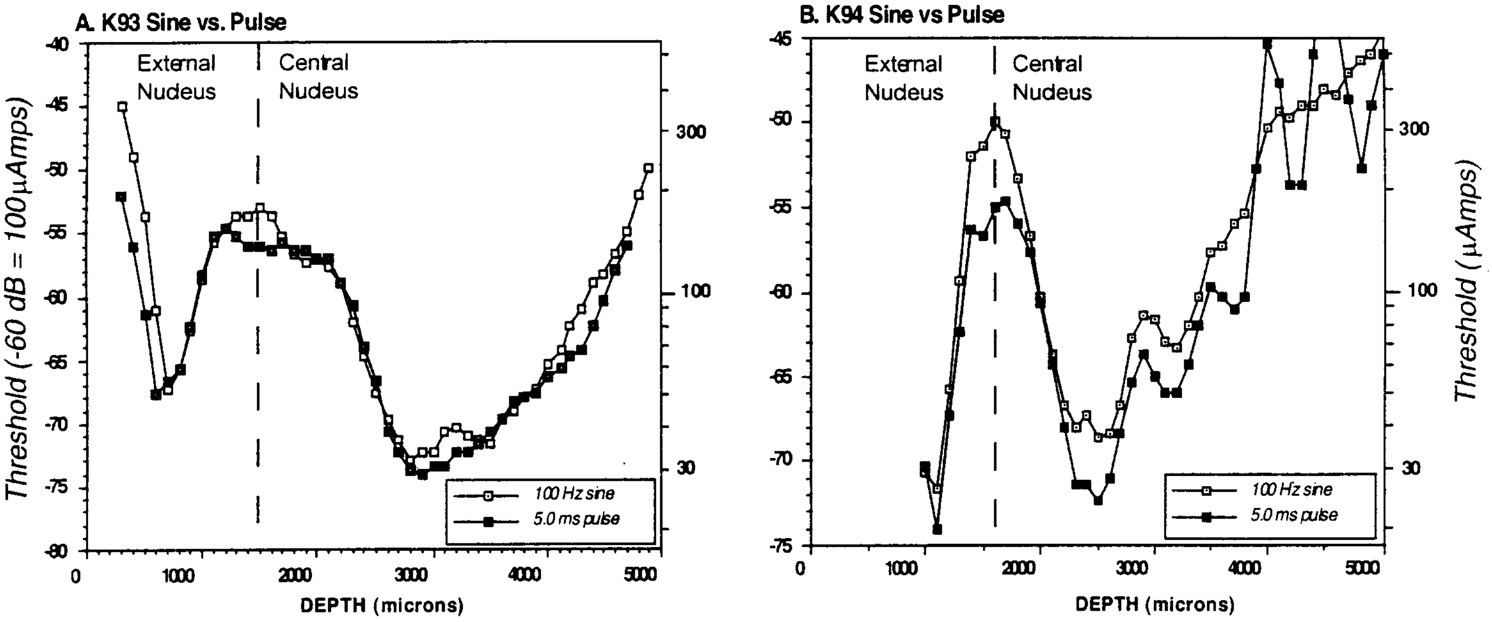

FIGURE 2. Spatial tuning curves (STCs) from single penetrations through the IC of two neonatally deafened cats. In each penetration two stimulus wave forms (100 Hz sine wave and 5 ms biphasic pulses) were used to evoke the multi-neuronal responses and to construct two STCs. These two wave forms evoke similar STCs indicating that wave form has only a minor effect on intracochlear excitation.

(18 dB for the pulse and 19dB for the sinusoid). Thus we can conclude that stimulus wave form has little effect on IC responses and STC parameters and we can infer that wave form has little effect on the threshold and spread of excitation in the auditory nerve .

In contrast to stimulus wave form, a stimulus parameter which strongly influences IC neuronal responses is phase duration. Figure 3 illustrates the systematic effect of pulse phase duration on STC width and thresholds. These STC were constructed from responses recorded in penetrations through the IC of two cats. In each cat a family of four STCs are illustrated. Each STC was produced using biphasic pulses with four different phase durations (0.2 ms, 1.0 ms, 1.7 ms and 5.0 ms). In both figures the shortest duration pulses (0.2 ms) required the most current to evoke a response, i.e., had the highest threshold (254 μAmps in A and 237 μAmps in B) and the longest phase duration (5 ms) had the lowest threshold (20 μAmps in A and 22 μAmps in B). It has long been known that total charge/phase (i.e., integration of current over time) strongly influences threshold. Therefore, it might not be unexpected that minimum threshold decreases systematically with lengthening phase duration (as illustrated by these data). Moreover, plotting threshold vs. duration for all IC penetrations in these two animals (Figure 4a) produces a family of curves with shapes that approximate classical strength-duration curves (Ranck, 1975). These curves indicate an average chronaxie of between 1 and 5 ms which is much longer than the chronaxie expected for myelinated axons (50 -150 μsec), but is close to that expected for unmyelinated axons or cell bodies (500 - 6000 μsec). Since these curves are derived from neonatally deafened animals in which there are few if any surviving peripheral axons, these data indicate that the cellular regions excited by our electrodes are the cell bodies of spiral ganglion cells.

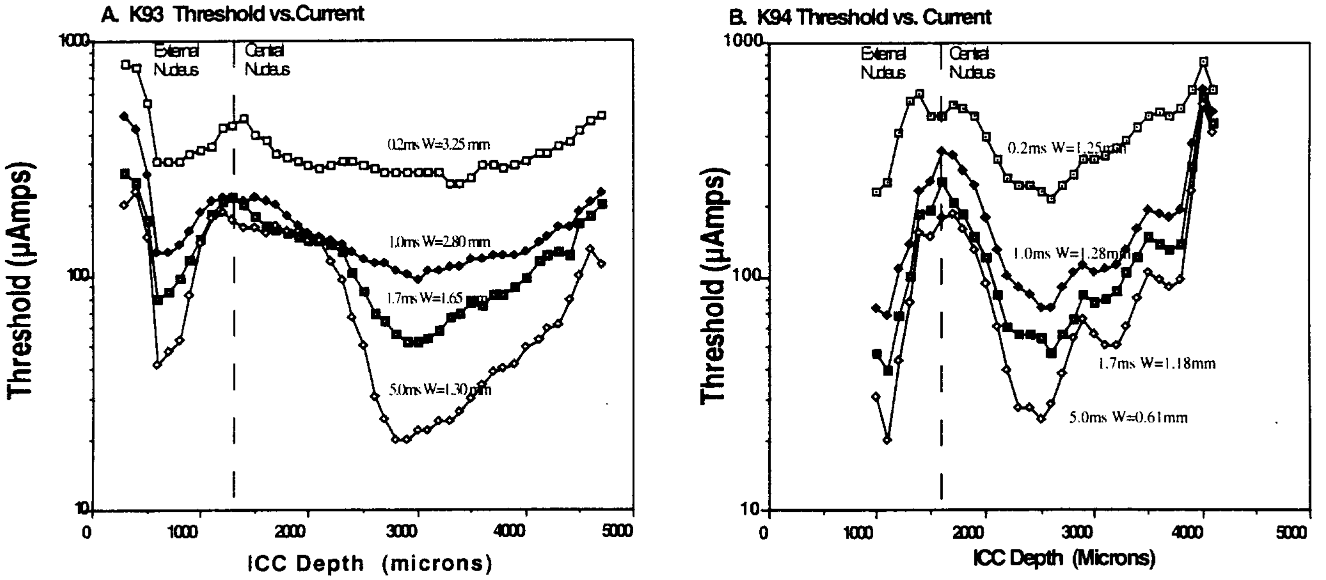

FIGURE 3. STCs from single penetrations through the IC of two neonatally deafened adult cats. In each penetration the biphasic pulses of the same four phase durations were used as stimuli. In both penetrations minimum threshold and STC width was directly related to pulse duration. The longest phase duration pulse produced an STC with the lowest minimum threshold and narrowest STC width and the shortest phase duration pulse produced an STC with the highest threshold and widest STC width.

Again the finding that threshold decreases as phase duration increases is not an unexpected result given the well understood principals of neuronal excitability phase duration is not expected to alter the spread current along the cochlear spiral (Ratay, 1987) . However, that STCs 6 dB width can increase as phase duration decreases is unexpected and is often seen in our experiments. In Figure 3A, STC width for the longest phase duration (5 ms) is relatively wide (1.3 mm) given a stimulus of this phase duration. The average 6 dB width for all STCs in cats of this type (chronically stimulated, neonatally deafened cats) using 5 ms/phase stimuli is approximately 1.1 mm. However, the STC width for the shortest phase duration signal (0.2ms) is 2.1 mm -- an increase of almost a factor of 2. The results illustrated in Figure 3A showing that STC width increases systematically as phase duration decreases are surprising since they indicate a differential and increasing spread of excitation along the cochlear spiral with decreasing phase duration. In this animal a 5 ms/phase pulse at 6 dB above minimum threshold activates approximately 1/3 of the ICC whereas a 0.2 ms/phase pulse activates almost the entire ICC at 6 dB above minimum threshold for that stimulus. In Figure 3b, the STC width for a 5 ms pulse is 0.61 mm; the width for a 0.2 ms pulse is twice that to 1.25 mm.

A plot of STC width as a function of phase duration for the same four penetrations is illustrated in Figure 4B. In every case STC width increased as phase duration decreased. However, the rate of decrease varies from animal to animal. In K93 the average width increases by a factor of nearly three fold, whereas in K94 the average increased by a factor of 1.7. Thus in some animals there are dramatic increases in STC width as a function of phase duration, whereas in others there is only a relatively small increase.

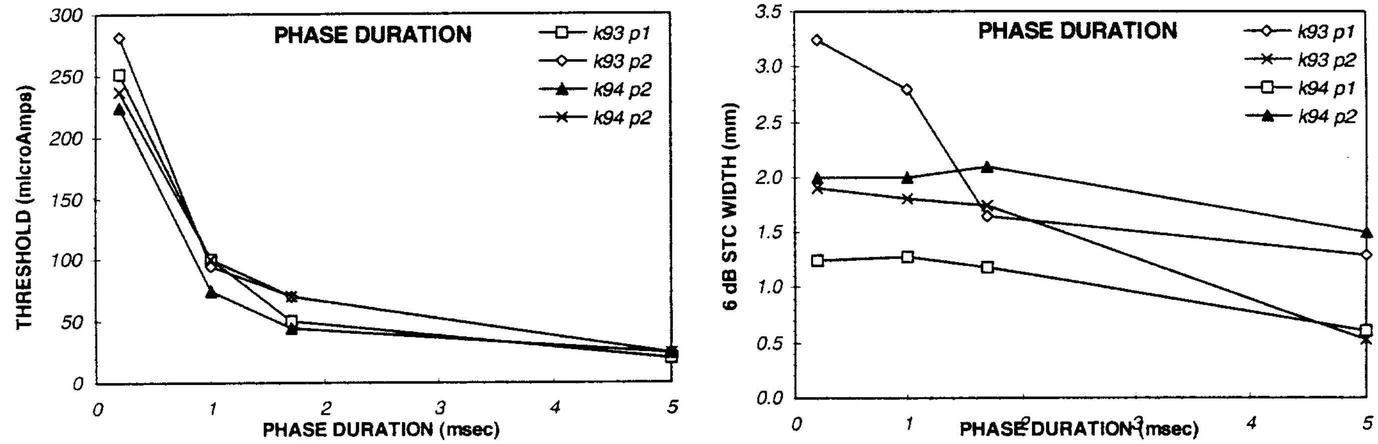

FIGURE 4. A) A plot of minimum threshold as a function of phase duration of biphasic pulses (0.2, 1.0, 1.7 and 5.0 ms/phase) for four penetrations in two neonatally deafened cats. Assuming an asymptotic threshold of approximately 20 μAmp, these curves indicate a chronaxie of 1 - 3 ms. B) A plot of STC width at 6 dB above minimum threshold for the same four penetrations. In all four penetrations STC width decreases consistently as pulse width increases. However, the rate of decrease varies from a factor of 1.2 to a factor of 3.

The variable influence of stimulus phase duration on minimum thresholds and STC widths for 67 penetrations through in IC of 29 cats is summarized in Figures 5 and 7. In these figures each point represents a penetration through the IC in which both minimum threshold and 6 dB width were determined for two STCs, one using a short phase duration signal (0.2 ms/phase biphasic pulse) and the other using a long phase duration signal (5 ms/phase 100 Hz sinusoid). In Figure 5A the minimum threshold for the short phase duration signals is plotted against threshold for long phase duration signals. This figure summarizes the relationship between minimum threshold for the two stimuli. As expected, and without exception, the minimum threshold for the short phase duration signal was higher (sensitivity was lower) than that for the long phase duration signal. On average the threshold for the short phase duration signal was -58 dB attenuation (126 µAmps) and that for the long phase duration signal was -73.5 dB attenuation (21 µAmps). The average difference was 15.5 dB, i.e., the average long phase duration STC had a threshold 15.5 dB higher than the average short phase duration STC.

This difference, however, varied widely. In some cases, the difference between thresholds for short and long phase duration signals was as little as 1 dB (near the 0 dB diagonal) and in others as great as 32 dB (above the 20 dB diagonal). This difference in minimum threshold was not related (or only weakly related) to the overall sensitivity of the animal. That is, the difference range for penetrations at the left of Figure 5a is not significantly different from that for

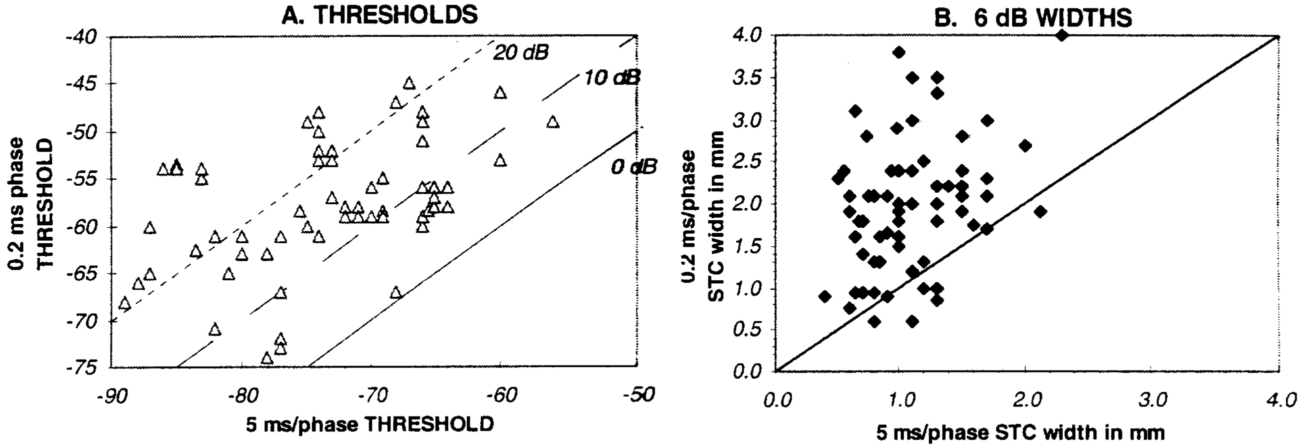

FIGURE 5. Comparisons of STCs evoked by short phase duration signals (0.2 ms/phase biphasic pulses) with those of evoked by long phase duration (5 ms/phase sinusoids) signals. STC were measured for both signals in 67 penetrations through the IC of 29 cats. A.) Minimum threshold (in dB attenuation with -60 equal to 100 µAmps) for short phase duration (0.2 ms/phase) signals is plotted against minimum thresholds for responses to long (5 ms/phase) phase duration signals in the central nucleus of the IC. Three iso-threshold difference contours are plotted: equal thresholds in both curves (labeled 0 dB); minimum threshold for 0.2 ms/phase signal 10 dB higher than that for 5 ms/phase signal (labeled10 dB); minimum threshold for 0.2 ms/phase signal 30 dB higher than that for 5 ms/phase signal (labeled20 dB). B.) STC width measured at 6 dB above threshold for short phase duration signals plotted against STC width for long phase duration signals for single penetrations through the IC. An equal width contour is plotted as the diagonal.

penetrations on the right. In Figure 5B STC widths for the 134 curves generated by stimulation using each of these two signals are compared. Clearly, STCs for short phase duration signals tend to be wider than those for long phase duration signals, i.e., they tend to lie above the equal width contour (diagonal line). Short phase duration STCs have an average width of 2.0 mm, whereas the average for long phase duration signals is 1.1 mm. Thus on average short phase duration STCs are nearly twice as wide as long phase duration STCs. This is exactly what one would expect from the curves illustrated in the previous two figures.

The data illustrated in Figure 5 suggest that on average a 0.2 ms/phase pulses require significantly higher current than a 5 ms/phase sinusoid to activate cochlear neurons and that the intracochlear spread of that activation increases more rapidly. Since we have demonstrated that sinusoids and pulses of identical phase duration produce STC of comparable width (Figure 2), these results suggest that longer phase duration signals activate the auditory nerve more selectively than short phase duration signals.

Although the average short phase duration STC is almost twice as wide as long phase duration STCs, there is great variability in the relative widths of STCs evoked by long and short phase duration signals. In some cases (Figure 3A) the short phase duration STCs are dramatically wider than long phase duration STCs, in some they are only somewhat wider (Figure 3B) and, surprisingly, in eight penetrations short phase duration signals produced STCs that had 6 dB widths that were equal to or narrower than those produced by long phase duration signals. One example of such an STC pair taken from a single penetration is illustrated in Figure 6. In this penetration stimulation with a long phase duration signal produced an STC with a minimum threshold of -78 dB attenuation (12 μAmps) and a 6 dB width of 1.1 mm. In the same penetration using the same electrode pair, stimulation with the short phase duration signal produced an STC with a minimum threshold of -74 dB attenuation (16 μAmps) and a 6 dB width of 0.9 mm. In a second penetration in this animal (not illustrated) comparable curve thresholds and widths were observed: The long phase duration signal produced an STC with a threshold of 15 μAmps and a 6 dB width of 1.2 mm, whereas the short phase duration signal produced an STC with a minimum threshold of 23 μAmps and a 6 dB width of 1.0 mm. Thus, in this animal, stimulation with the short phase duration signals produced STCs which had slightly higher minimum thresholds and slightly *narrower* 6 dB widths than those produced by stimulation with long phase duration signals. These results indicate that in some unusual cases a 0.2 ms/phase pulse can produce a more selective activation of the auditory nerve than long phase duration signals even though it requires greater minimum peak current to evoke that activation.

Thus there is great variability in the relative selectivity of long and short phase duration signals. If we consider only those penetrations in which stimulation with a 5ms/phase stimulus evokes an 1 mm wide STC, stimulation with a 0.2 ms/phase stimulus can evoke STCs that are as narrow as 0.5 mm (a ratio of 0.5) or an STC that is as wide as 3.7 mm (a ratio of nearly 4). What can account for this range of variation? A comparison of the curves illustrated in Figures 3 and 6 provides a clue. In Figure 3 the STCs produced by stimulation with 0.2 ms/phase signals are broad and their minimum thresholds are high relative to those of the 5 ms/phase STCs. In Figure6 the 0.2 ms/phase STC is relatively narrow and its minimum threshold is relatively low. This suggests that *relative* STC width and *relative* minimum threshold are related. This relationship is illustrated in Figure 7 which plots the difference in STC width as a function of the difference in threshold. There is a clear correlation ($R^2 = 0.45$) between the difference in threshold and the difference in width for STCs generated in the same penetration using short and long phase duration signals. Comparing the difference between short and long phase duration STCs normalizes them for common shifts in sensitivity and selectivity that occur from animal to animal. For example, most of these STCs were measured in chronically stimulated and/or long deafened cats. These animalshave been previously demonstrated to have significant changes in both sensitivity (minimum threshold) and selectivity (STC width) of intracochlear stimulation (Snyder et al., 1990, 1991; Leake et al., 1995). The correlation between the difference in threshold and the difference in STC width indicates that if the two sets of STCs are corrected for threshold differences, their widths are more similar and much of the variability seen in Figure 5b is due to variance among animals.

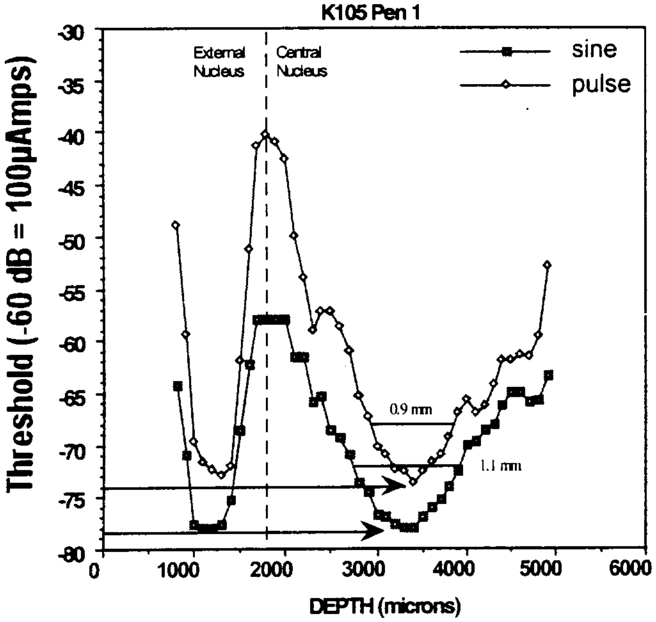

FIGURE 6. STCs produced by stimulation using an 0.2 ms/phase biphasic pulse and an 5 ms/phase (100 Hz) sinusoid in one penetration through the IC central nucleus (ICC) of cat K105. The minimum thresholds are -74 dB and -78 dB (indicated by the horizontal arrows). The STC widths at 6dB above minimum threshold are 1.1 mm and 0.9 mm (indicated by the horizontal lines) and the associated numbers.

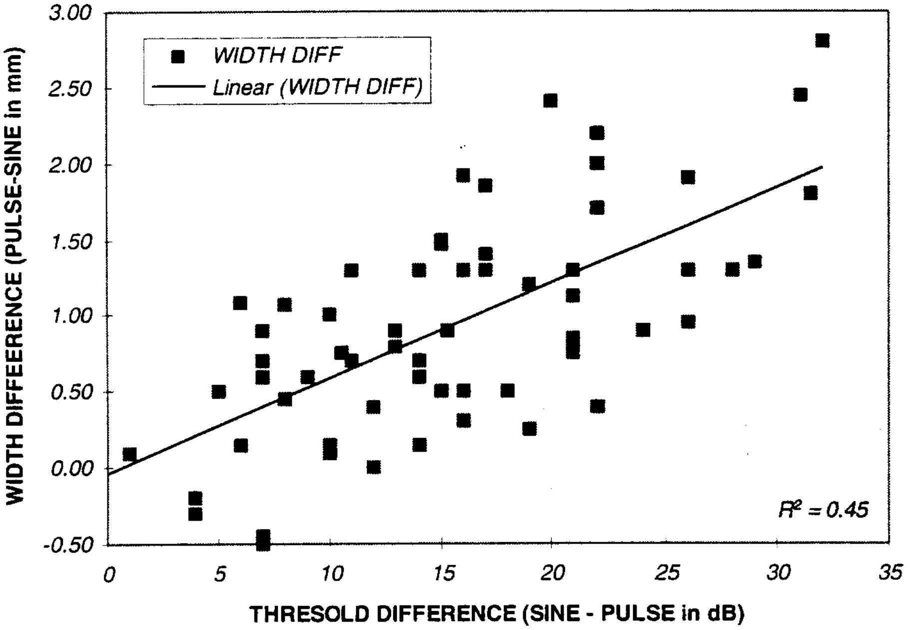

FIGURE 7. The difference measures for long and short phase duration STCs. Width difference (0.2 ms/phase STC width -5 ms/phase STC width) is plotted against minimum threshold difference for 67 penetrations (1 point/ penetration) in which both curves were measured.

DISCUSSION:

In this report we have examined the effects of both stimulus wave form (sinusoids vs. pulses) and phase duration on sensitivity and selectivity of auditory nerve activation from intracochlear electrical stimulation. We have used indirect measures of both sensitivity and selectivity (the minimum current to evoke a neural response in the ICC and the width of ICC spatial tuning curve), however, the validity and reliability of these our measures has been demonstrated previously (Snyder et al., 1990; 1991; Leake et al., 1995. In this report we have shown that signal wave form (sinusoid vs. pulse) has only a small effect on ICES sensitivity, given the difference in total charge delivered between the two signals, and little or no effect on ICES selectivity. However, signal phase duration has a strong effect on both of the these important parameters. As phase duration becomes shorter the current necessary to evoke a response increases and the apparent selectivity of the stimulus decreases. A 0.2 ms/phase signal requires a peak current that is 15.5 dB higher than a 5 ms/phase signal and evokes a response that is approximately half as selective.

We believe that these observations are important because many cochlear implant processors use trains of very short phase duration pulses as carriers to encode speech. For example, the highly successful CIS processing strategy consists essentially of amplitude modulation (AM) of carriers composed of 0.1 - 0.05 ms/phase pulses delivered at high (500 - 2500 pps) repetition rates. The SPEAK strategy uses amplitude modulation of pulses that are 0.15 ms/phase. Results of our electrophysiological mapping studies suggest that this type of signal would require high current levels to reach threshold (i.e., to evoke a percept in a CI subject) and would broadly excite the auditory nerve in that subject even at low levels only a few dB above threshold. Thus stimulation using these signals should be subject to very high levels of channel interaction, have very narrow dynamic range and CI users should report very poor place pitch using them. However, the results of patient studies fail to confirm this prediction (Shannon, 1983; Townshend et al., 1987; McDermott and McKay, 1994).

How can we resolve this discrepancy? One hypothesis is that short phase duration stimuli might be more spatially selective when they delivered at relatively high repetition rates (>100 pps) than when they are delivered at lower rates (2-3 pps). Although this suggestion is possible, it seems unlikely since pulses delivered at high repetition rates suppress neural responses in the IC rather than evoking them at lower threshold. Another hypothesis, suggested by the data in Figures 6 & 7, is that this discrepancy in spatial tuning between short and long phase duration stimuli is simply a matter of scaling and would disappear if the data were plotted appropriately.

In Figure 8A the spatial tuning curves for two stimuli are plotted for one penetration through the cat IC. In this figure *threshold current* data from one penetration is plotted on a log scale as a function of penetration depth, as it has been in all previous STC plots. However, it is reasonable to argue that threshold current is not the appropriate value to plot. Rather one should plot *charge/phase,* since total charge/phase (the integral of current over time) is the parameter that depolarizes neurons. In Figure 8B the threshold current is converted to threshold charge/phase and the data re-plotted. As expected converting the data to charge/phase more closely

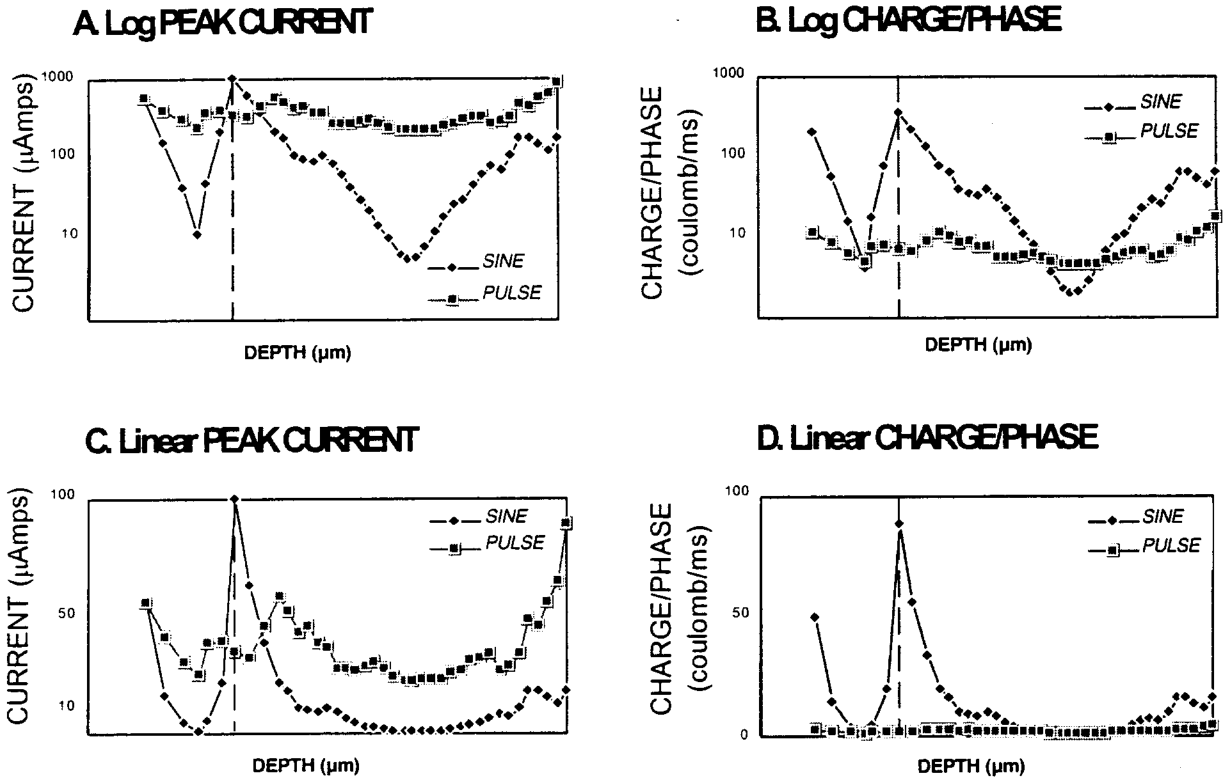

FIGURE 8. Plots of identical STC data for short (pulse) and long (sine) phase duration signals. The left hand column (A and C) STCs are plotted using peak current. The right hand column (B and D) are plotted as total charge. In the upper row (A and B) the data are plotted on a log scale along the ordinate. In the bottom row (C and D) the data are plotted on a linear scale.

approximates the minimum thresholds of the short phase duration (pulse) stimulus and the long phase duration (sinusoidal) stimulus. However, the relationship in terms of spatial tuning is unchanged. The long phase duration stimulus is still distinctly tuned and short phase duration stimulus still shows relatively poorly tuning. It can also be argued that perhaps the difference in tuning is due to scaling of the ordinate. Perhaps the data should be plotted on a linear scale rather than a log scale. In Figure 8D the charge/phase data is re-plotted on a linear scale. Plotting the data in this way decreases the apparent tuning in both curves but does not alter the discrepancy in tuning between the two stimuli. In Figure 8C peak threshold current is plotted on a linear scale and the apparent tuning of the two stimuli is now equalized, *but both stimuli appear to be equally poorly tuned*! These plots suggest that we are caught in a sort of 'Hobbson's choice'. Either long phase duration signals are more spatially selective than short phase duration signals or both long and short phase duration signals are equally poorly tuned spatially and are equally unsuitable for selective activation of the auditory nerve.

In Figure 9 the identical current data on a log scale (like 8A) are plotted, but the values have been normalized by subtracting minimum threshold current and adding 1 μAmp (since subtracting at minimum current from the minimum current produces a zero which cannot be plotted on a log scale). This normalization procedure (in effect plotting intensity in dB re threshold) makes an enormous difference. Using this normalized data, both long and short phase duration signals are sharply tuned. Indeed, the short phase duration STC is even slightly more sharply tuned than the long phase duration STC. They also have a similar dynamic range in μAmps. Thus these normalized data make it clear that, if there is no difference in the spatial tuning between long and short phase duration signals (i.e., no difference in the channel interaction or place pitch discrimination of these signals), then the appropriate way to plot (think about) intracochlear electrical stimulation is in terms of peak current (μAmps) above threshold on a log scale. Thus an increase in the stimulus current by 30 μAmps above minimum threshold might produce the same increase in perceived loudness and channel interaction regardless of the absolute stimulus level. The psychophysical consequences of this 30 μAmps increase might be the same whether it occurs between 10 and 40 μAmps (a 12 dB step) using long phase duration signals or between 510 and 540 μAmps (a 0.5 dB step) using short phase duration signals. Assuming that this normalization is appropriate, it suggests that short phase and long phase duration signals will have similar dynamic ranges when measured in psychophysical units (e.g., just discriminable steps) but will have vastly different dynamic ranges when measured in absolute unit (e.g., dB re 1 or 100 μAmp). Thus the compressed dynamic range of many CI subjects may be simply due to the fact that their thresholds are high and dynamic range is measured in dB relative some absolute value.

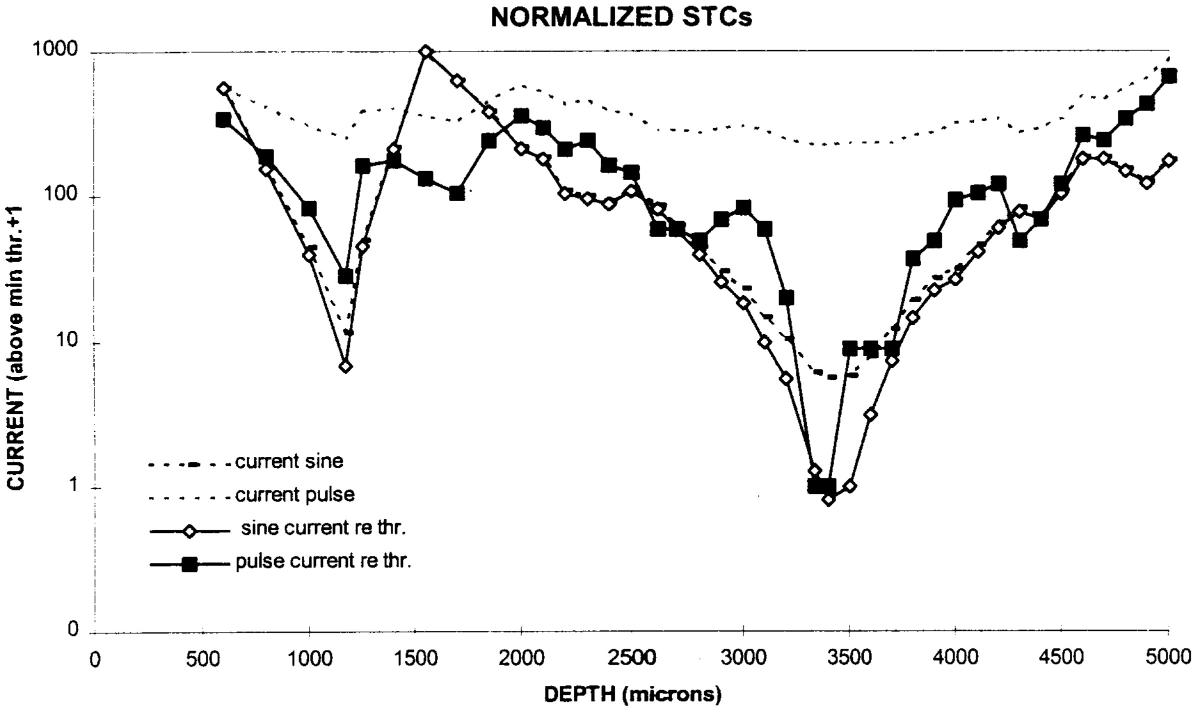

FIGURE 9. Spatial tuning curves evoked by short and long phase duration signals. In the normalized STC s (solid lines) the threshold values (plus one μAmp) are normalized by having the minimum threshold current subtracted from them. The non-normalized STCs (dotted lines) have been included for comparison.

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