Advances in Prosthetic Devices for the Deaf
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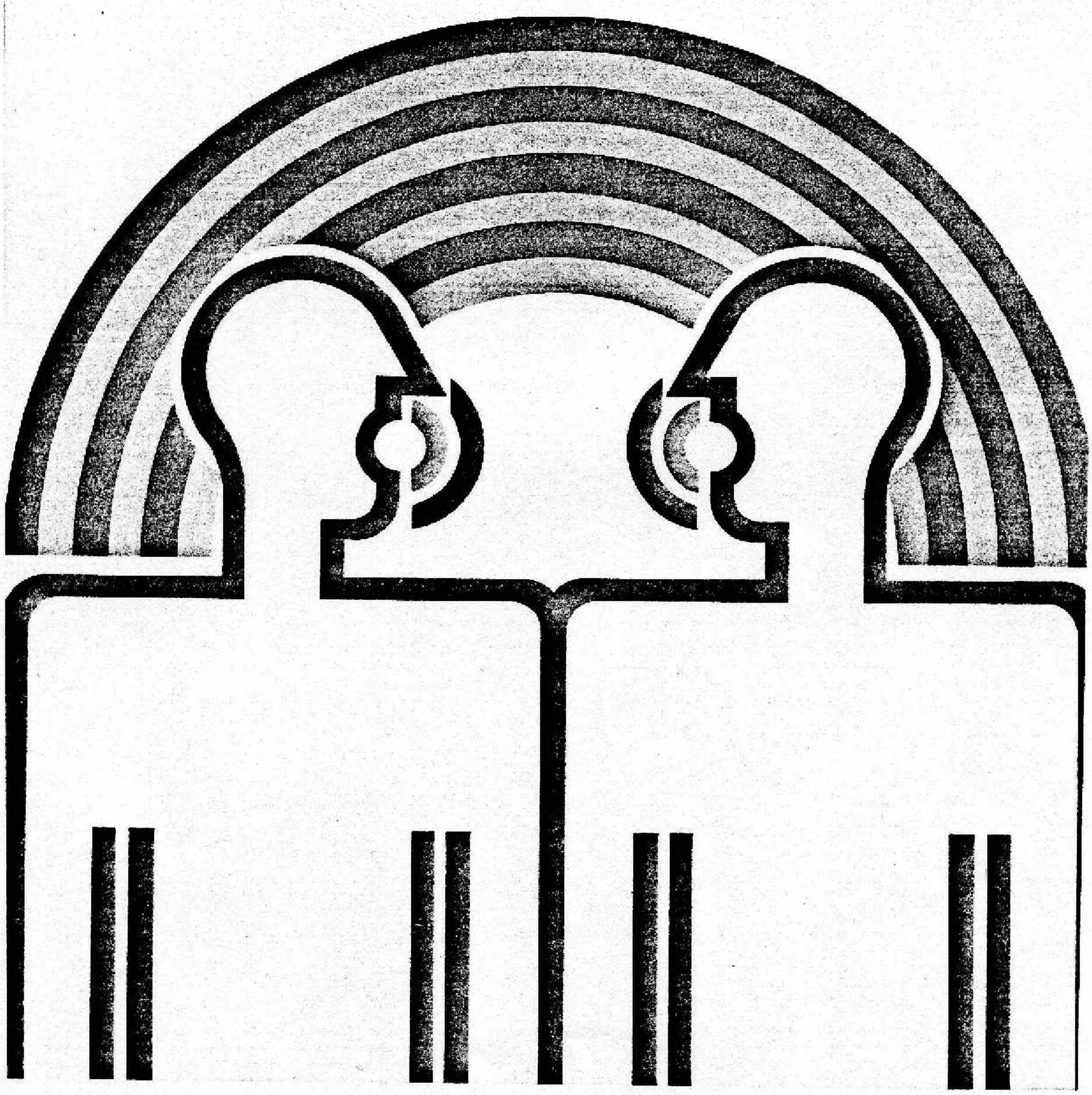

Progress in Development of Implantable Multielectrode Scala Tympani Arrays for a Cochlear Implant Prosthesis ....

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Introduction

The ultimate objective of cochlear implant research is to develop an electrical stimulation prothesis that provides a level of appropriate information to the central nervous system that is necessary and sufficient to encode speech as intelligible. The UCSF cochlear implant research group has directed much of its basic research effort toward resolving questions related to the interfacing of multielectrode arrays with the auditory nerve array. Two of the fundamental interface questions addressed by the research group will be considered. First, what stimulating elements of multichannel stimulating arrays might provide information necessary and sufficient for the encoding of intelligible speech? Second, what is safe to do, i.e., can "ideal" multielectrode arrays be safely applied in deaf patients? Substantial progress has been made in answering these two fundamental, multifaceted questions. They indicate, on a first level, that appropriate stimulation can probably be effected with appropriate multielectrode arrays, and that stimulation with these "ideal" arrays could provide significant speech intelligibility; and that, with reservations, such multielectrode arrays can be applied without their implantation or long term stimulation resulting in further loss of surviving auditory nerve fibers in implanted patients.

Excitation Patterns for Implanted Intracochlear Electrodes Defined in Inferior Colliculus Electrode Mapping Studies

Two basic experimental strategies have been used to define cochlear excitation patterns evoked by various intracochlear electrodes (with different contact surface areas and geometries, different interelectrode separations, different locations). In one long experimental series, multielectrode arrays were implanted chronically into the cochleas of prior-normal or neomycin-deafened cats. A few to many months later, an acute electrophysiological experiment was conducted to define excitation patterns evoked by stimulation with different electrodes of these long-implanted intracochlear electrode arrays. Excitation patterns were determined in mapping experiments conducted in the binaural excitatory-excitatory region of the central nucleus inferior colliculus. In this cochleotopically organized region, neurons are excited maximally with input derived from corresponding locations in the two cochleas. The cochlear site from which a given inferior colliculus neuron derives its input from both ears can be defined by simply determining the "best frequency" (the frequency at which the neuron is driven at lowest threshold) for stimulation of either ear. That is, in a normal cat, the best frequency for any given excitatory-excitatory neuron in the central nucleus is approximately the same, for stimulation of either ear. In mapping excitation patterns evoked by electrical stimulation with given elements of different intracochlear multielectrode arrays, the best frequency of a neuron to stimulation in the ipsilateral normal cochlea was defined, and then the threshold response to electrical stimulation of that neuron (deriving its input from the same position in the contralateral, implanted ear) was defined. Given the systematic spatial representation of cochlear place (sound frequency) within the central nucleus, it was possible to map the electrical response threshold for any given electrode as a function of location across the spiraling auditory nerve array in the cochlea, by determining ipsilateral best frequency and contralateral threshold for electrical stimulation for a large series of neurons spanning the entire frequency range. The results of these experiments, again, were maps of cochlear excitation (i.e., a definition of electrical stimulation threshold as a function of cochlear place) for given chronically implanted intracochlear electrodes.

The results of some of these experiments have been reported in detail (Merzenich, 1975; Merzenich & White, 1977; Schindler, et al., 1977; White, 1978). Among other results were the following: 1) Discrete, restricted, relatively low threshold stimulation of the auditory nerve array can be effected with stimulation with an appropriately positioned bipolar electrode with an interelectrode separation of about 0.5 to about 1.5 mm (Figure 1). With broader interelectrode separations, excitation regions grow more and more rapidly in extent as a function of I. In this experimental series, with well-positioned electrodes with interelectrode separations of 0.5-1.5 mm, the mean change of threshold as a function of distance across the auditory nerve array was about 12.4 dB/octave in the cat, (i.e., 12.4 dB/3mm), which would translate to about 20.5 dB/octave in man (see Figure 1). 2) Discrete excitation could not be effected with "monopolar" intracochlear electrodes (i.e., with stimulation between a cochlear electrode and an external electrode) of any size or in any location. This is an apparent consequence of the fact that the lowest impedance path is through the body of the auditory nerve. (Further, Rushton demonstrated many years ago that if the path of current parallels the axis of nerve fibers, lowest threshold excitation results.) In any event, excitation patterns for monopolar electrodes introduced at different cochlear locations (or of different sizes) were invariably broad and varied little. The entire auditory nerve was always stimulated with monopolar electrodes at levels 10-15 dB above threshold. 3) Discrete excitation could also not be effected with use of any tested intracochlear common-grounding scheme. This was an apparent consequence of the fact that the surface impedance of small intracochlear electrodes was high relative to the tissue impedance between electrodes. 4) On the basis of the form of strength duration curves, it was concluded that excitation at threshold was of myelinated nerve, i.e., of surviving dendrites or surviving myelinated ganglion cells. Considering excitation patterns in "misplaced" electrode pairs and simple equipotential field models (White, 1978) it was concluded that the excitation pattern evoked by bipolar pairs is a simple function of the proximity of electrode contact surfaces from myelinated dendrites or soma.

studied cats were judged to be totally deaf for a period of a few weeks to about two years when the acute neurophysiological experiment was conducted. In other experiments, cats were deafened just prior to the acute neurophysiological experiment by intracochlear injection of neomycin (via the round window). In both experimental paradigms, hearing losses were tracked by recording acoustic brain stem evoked responses (BSERs) in the period following the injection of neomycin.

These prepared deaf cats were anesthetized, and the basal 10-11 mm of the scala tympani opened surgically. Excitation patterns were then defined for a variety of electrodes introduced into different locations re the surfaces of the scala. The electrode mapping procedures employed in these experiments made use of recording of BSER intensity functions. Earlier experiments (Merzenich & White, 1977; White, 1978; Merzenich, et al., 1978) had revealed that the amplitudes of BSER responses were a simple (nearly linear) function of spread of excitation across the auditory nerve array. This observation was initially made in experiments that made use of simultaneous inferior colliculus mapping (described earlier) to define spread of excitation across the nerve array as a function of current level, with recording of BSERs at the same levels of I. (It has subsequently been confirmed by a second independent electrode mapping technique developed by White, et al., 1978). Thus, the slope of a BSER intensity function defining the amplitude of the BSER as a function of I is a simple expression of the rate of spread of excitation across the auditory nerve array as a function of I.

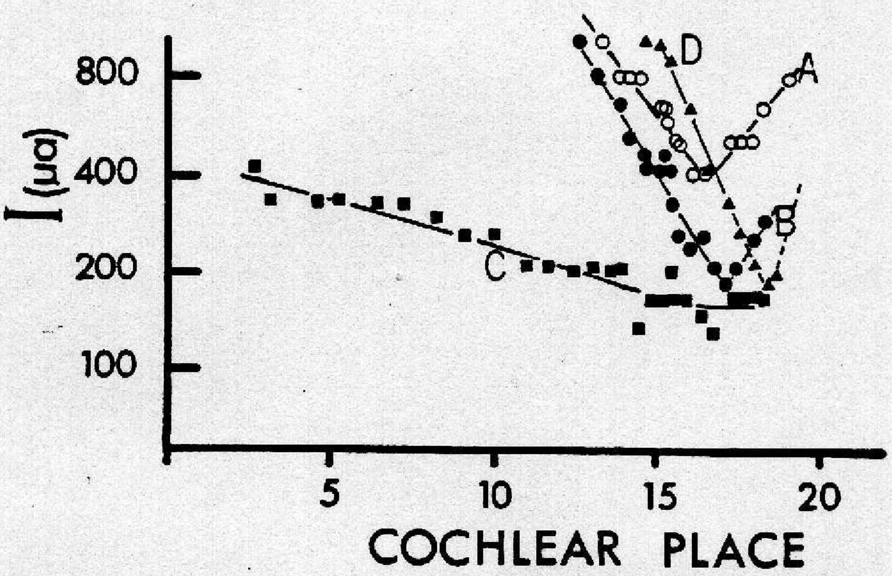

Figure 1. Spatial excitation patterns derived by use of the inferior colliculus electrode mapping technique for representative scala tympani electrodes. Stimuli were 100 μsec/phase biphasic pulses. Curves in A and B were derived with excitation between two electrode pairs, both separated by interelectrode distances of about 2.0 mm. Curve C was derived with excitation between one of these contact surfaces and a distant (middle ear) "ground" (a "monopolar" configuration). Curve D was derived with stimulation of a well-positioned bipolar scala tympani electrode with an interelectrode separation of 0.5 mm.

Brain Stem Evoked Response Electrode Mapping Studies

These experiments have been amplified and extended in recent studies of excitation patterns in dissected cochleas in acute neurophysiological experiments. These experiments have been conducted in neomycin deafened cats. In some preparations, the cats were deafened by intramuscular injection of neomycin over a period of 7-10 days. Different

The practical use of BSER mapping procedures is illustrated in Figures 2-4. A typical BSER intensity series is illustrated in Figure 2. This series illustrates the growth of BSER amplitude as a function of I for a favorably positioned bipolar electrode with an interelectrode separation of about 1.2 mm. The rms amplitude of this BSER intensity series is represented by curve B in Figure 3. The response threshold was 105-106 dB (113 dB = 1mA). The relatively gradual growth of response magnitude reflects the relatively slow spread of excitation across the auditory nerve array as a function of I, for this relatively discretely exciting electrode. Curve A was derived with a second bipolar electrode in the same region (and with the same orientation) in the same experiment, but with an interelectrode separation of 2.7 mm. The relatively rapid growth of the magnitude of the response reflects the more rapid spread of excitation across the auditory nerve array as a function of I, for this less discretely exciting electrode. Given these elementary experimental techniques, excitation patterns can be rapidly estimated, for electrodes of any shape or type introduced at any intracochlear location. We have conducted extensive experiments, for example, in which excitation patterns have been defined as a function of intracochlear location; as a function of the size of contact surfaces; and as a function of interelectrode separation of bipolar electrodes introduced into the scala tympani.

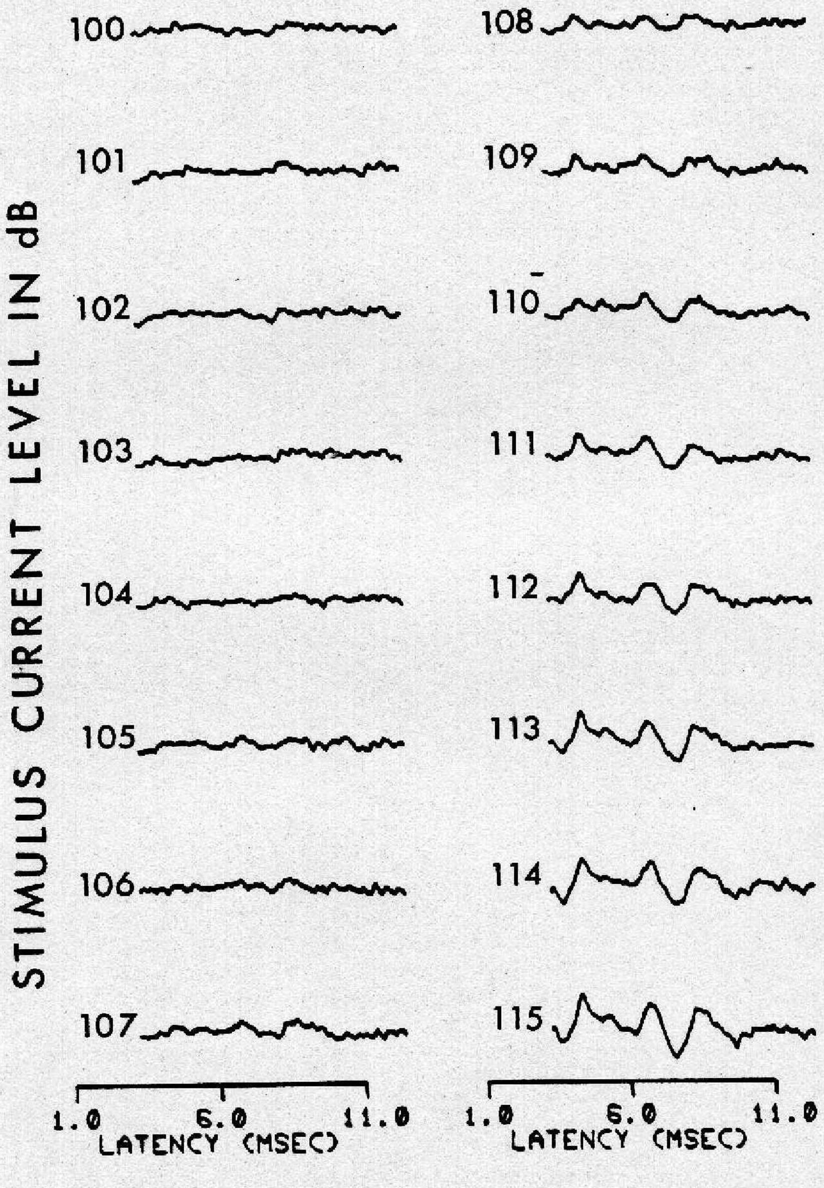

Figure 2. Cat BSERs (N = 1000) recorded from ipsilateral electrodes ($C_z - A_1$) as a function of stimulus current level (113 dB = 1 mA). Biphasic electrical pulses (100 microseconds each phase) were presented at a rate of 20/sec. Responses were derived for bipolar stimulation using longitudinally arrayed electrodes (open circles in Figure 5A) with an interelectrode separation of about 1.2 mm.

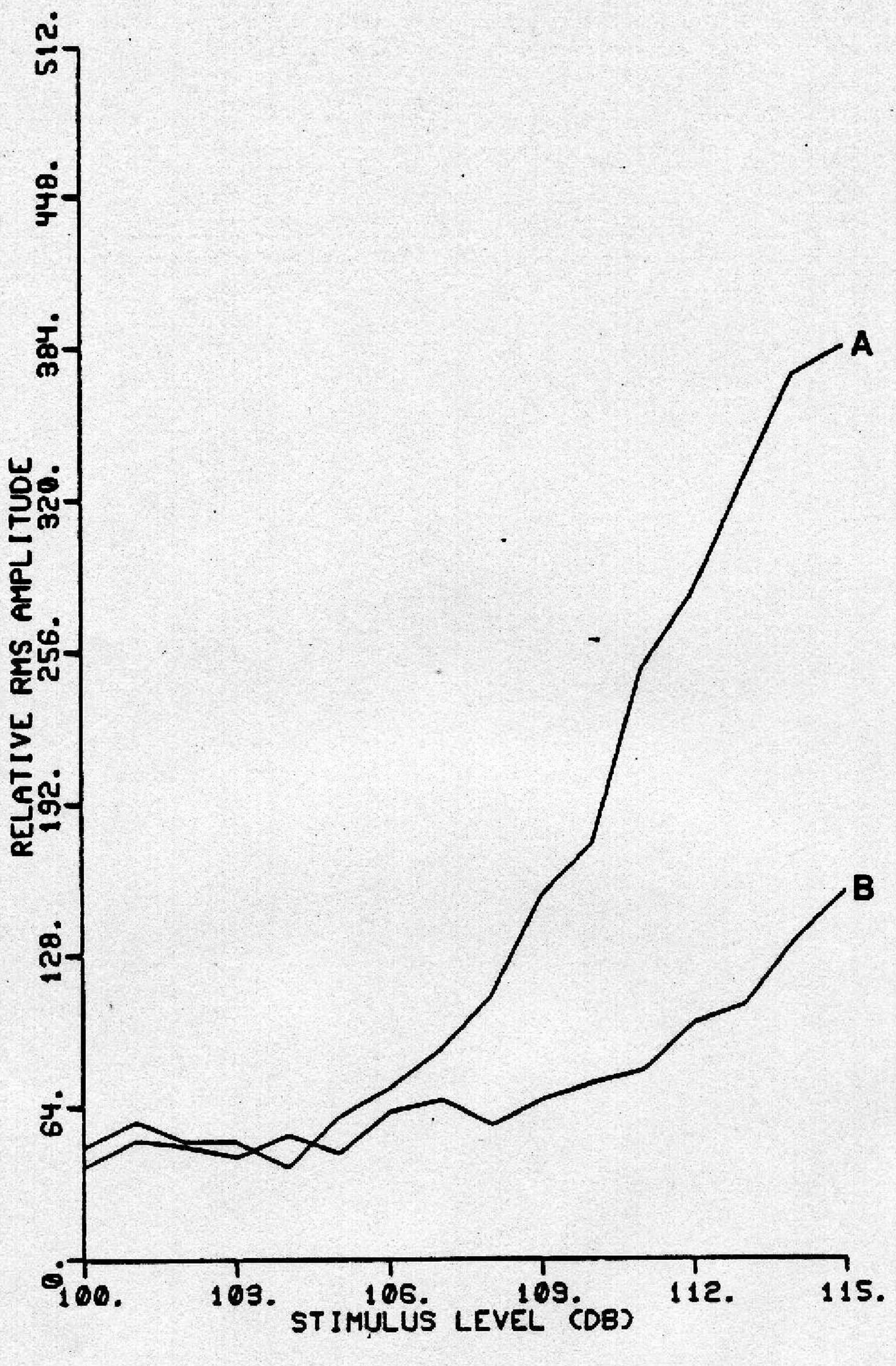

Figure 3. Relative rms amplitudes of cat BSERs (N=1000) as a function of a stimulus current level, for two different bipolar electrodes separated longitudinally along the medial edge of the bony spiral lamina (the optimum mediolateral location for stimulation in this "dendriteless" cochlea). The interelectrode separation for curve "B" was about 1.2 mm; for curve "A," it was about 2.7 mm. The intensity series for curve B is illustrated in Figure 2. Note that the thresholds for auditory nerve stimulation for these two bipolar electrodes were nearly identical.

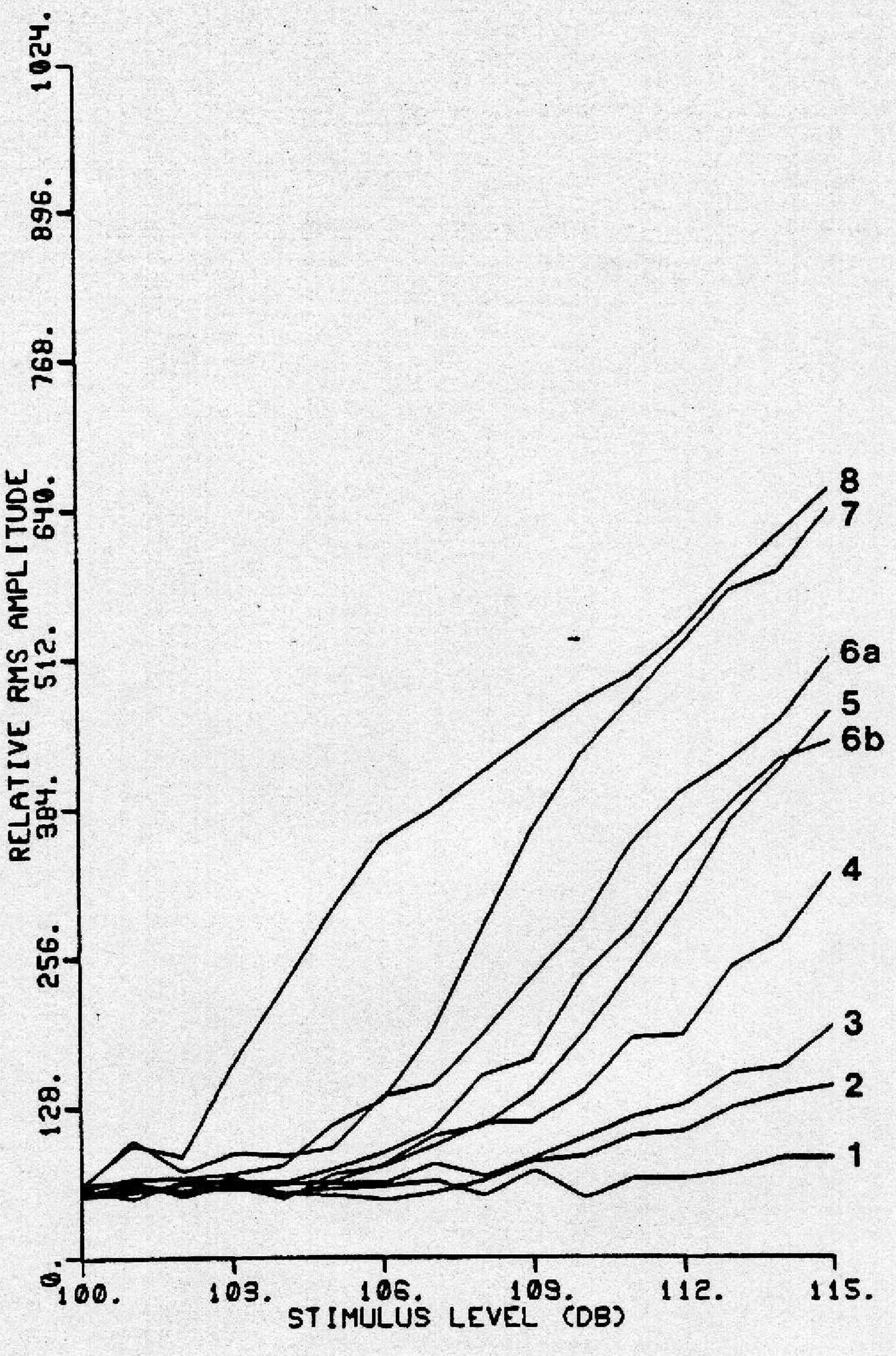

Figure 4. Relative rms amplitudes of cat BSERs (N = 1000) as a function of stimulus current level and electrode placement. Ipsilateral BSERs were recorded during biphasic electrical stimulation. Stimulating electrodes were positioned parallel to the long axis of the basilar membrane in locations illustrated in Figure 5A. Interelectrode distance was systematically increased, from a minimum of about 0.3 mm (curve 1) to a maximum of about 9.2 mm (curve 8). One electrode in each bipolar pair was maintained in a constant reference position ("R" in Figure 5A); the positions of the second electrodes of each pair is marked in Figure 5A by the number corresponding to the curves.

One example of a parametric cochlear mapping experiment of this kind is illustrated in Figure 4. These nine intensity series were derived for eight different interelectrode separations, with electrodes arrayed longitudinally along the medial edge of the bony spiral lamina (Figure 5A) in a long term neomycin deafened cat. The electrode separation was a systematic function of interelectrode separation (Figure 6), i.e., as bipolar electrodes were separated, the rate of excitation changed systematically.

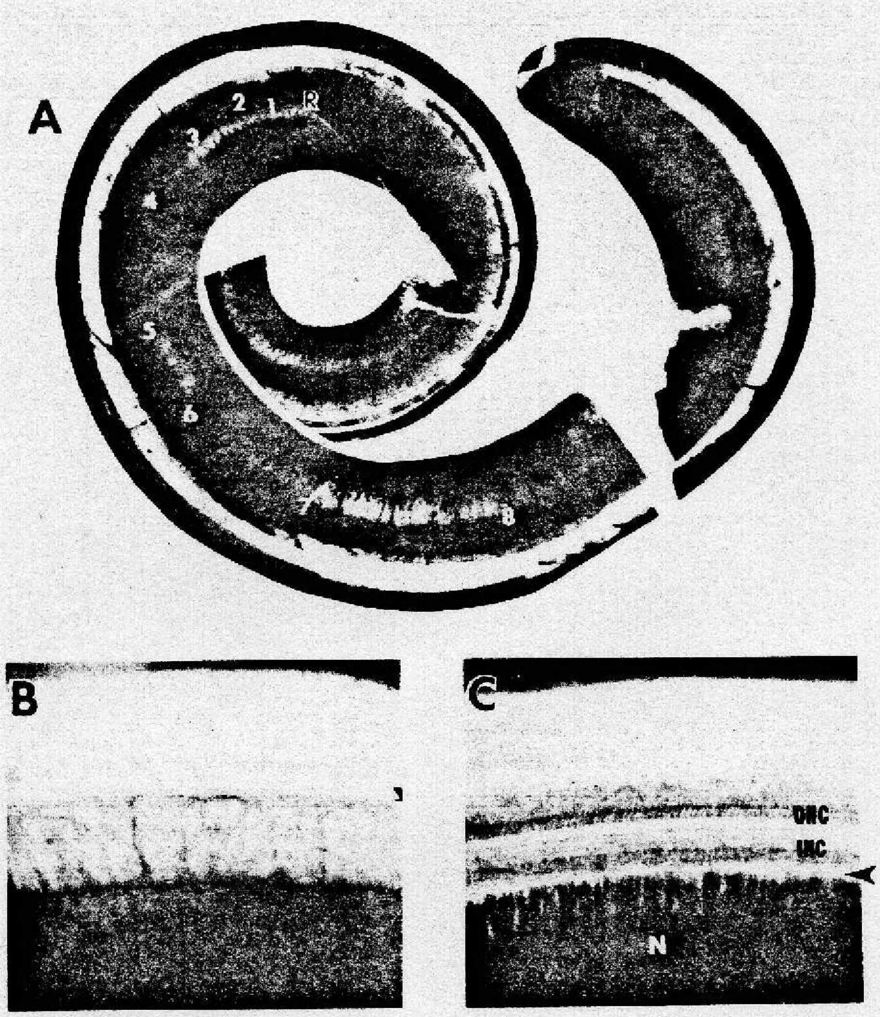

Figure 5. (A) Dissected cochlea from a cat studied 1 year and 7 months after injection of 50 mg/kg/day of neomycin sulfate for 10 days. A higher magnification of the region about 10 mm from the cochlear base is illustrated at the lower left (B). A corresponding section from a normal cochlea is shown at the lower right (C). The level of the habenula (where auditory nerve fibers lose their myelin and enter the organ of Corti) is indicated in B and in C by arrows. Outer hair cells (OHC) and inner hair cells (IHC) were completely absent in this long surviving neomycin deafened cat. Few or no dendrites (N) were present in the basal cochlea, where mapping experiments were conducted in this cat. The numbers and symbols represent positions of stimulating electrodes in this cochlea for the experiments illustrated in Figures 2-4 (see text for details).

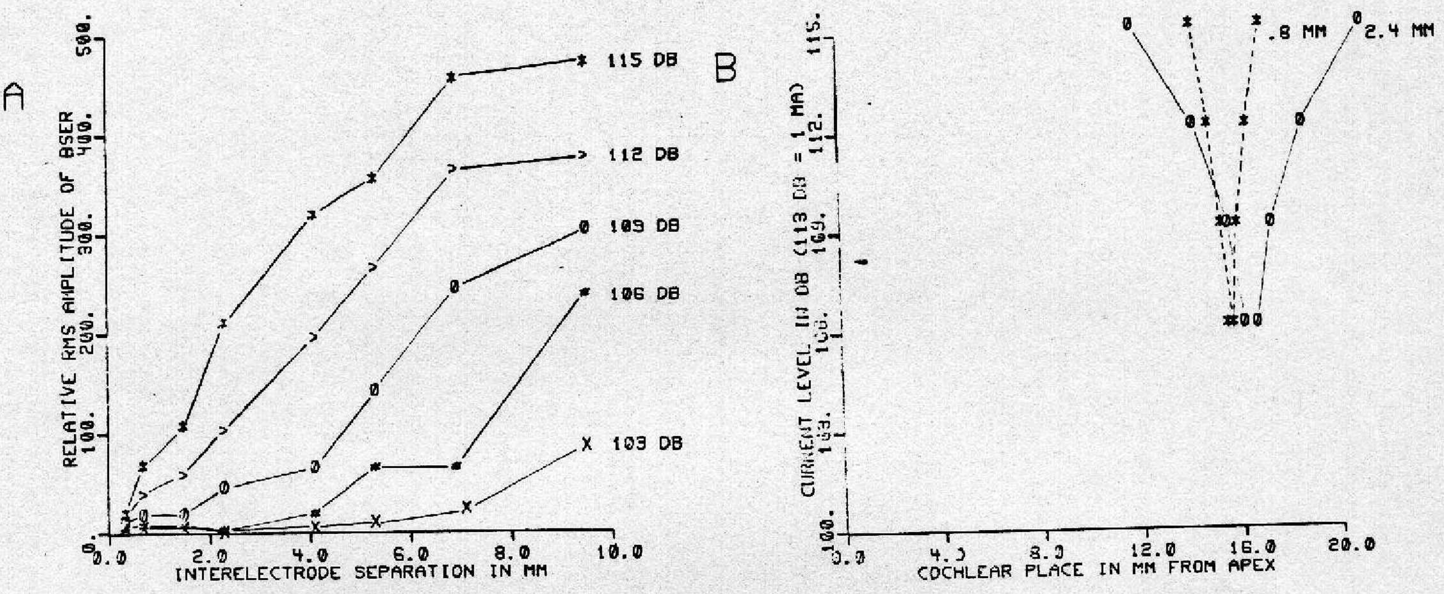

Figure 6. (A) Magnitude of BSER's derived with stimulation of bipolar electrodes, as a function of interelectrode separation for 200 micron contact surfaces separated by distances varying from about 0.44 mm to about 9.6 mm. Functions are shown at 5 levels of I.

Figure 6. (B) Estimated cochlea excitation maps for two of the electrodes (indicated by numbers) whose intensity functions are illustrated in Figure 4. These functions were derived with reference to the nearly linear relationship between BSER amplitude and spread of excitation within the auditory nerve array recorded with electrical stimulation (see text).

Given other direct mapping data, it was possible to translate the spread of excitation as a function of I for intensity series such as those shown in Figure 4 directly into excitation maps (see Figure 6). Thus, for example, with an interelectrode separation of 0.8 mm (curve 2) the excitation spread approximately 1.4 mm at a stimulus level 10 dB above threshold. (Referenced to a normal cat cochlea, this translates to a slope of about 20 dB/octave.) With an interelectrode separation of about 2.4 mm (curve 4), excitation had spread nearly 7 mm at a level 10 dB above threshold. (Referenced to a normal cat cochlea, this translates to a slope of about 4.3 dB/octave.) With the two largest illustrated separations (about 7 and 9.6 mm), the majority of auditory nerve fibers were engaged at stimulus levels 10 dB above threshold. Note that the response threshold changes relatively little, until very wide interelectrode separations are reached.

These experiments have been conducted with electrodes in a variety of locations within the scala tympani. (Some of these results have been reported by Merzenich, et al., 1978.) Experiments have been conducted in cochleas in which nerve fiber destruction is severe (as in the case illustrated in FiFigure 4 and 5); and in cochleas in which nerve fiber distinction is not extensive, but hair cell loss is complete or nearly complete. These experiments, taken together, have revealed some of the characteristics of the "ideal" intracochlear electrode.

On a first level of understanding, these electrode mapping experiments indicate that the "ideal" electrode elements are longitudinally or transversely oriented bipolar electrodes, with electrode separations of the order of a millimeter. Electrodes should be positioned over the bony spiral lamina in a relatively medial position to insure that ganglion cells in "dendriteless" regions of the cochleas are excited at low current levels. Electrodes must be positioned as near to these surfaces of the scala as is possible. Considerations of size and geometry are complex, but it is evident that the physical size of electrode contact surfaces is not a critical determinant of electrode excitation patterns until inter-contact (edge to edge) distances become less than about 0.5 mm (with shorter inter-contact distances, threshold for electrical stimulation is sometimes elevated). Similarly, when the diameter of balled electrodes exceeds about 300 microns, threshold becomes significantly elevated.

In what sense are these scala tympani bipolar electrodes ideal? The definition of an electrode as "ideal" is based upon a simulation model of a cochlear implant prosthesis. That is, an "ideal" electrode effects sufficiently restricted excitation as a function of I to allow for translation of excitation into the spatial equivalent of normal cochlear excitation patterns generated by simple tones. There are several basic factors to consider, in effecting this simulation. First, excitation need only be relatively discrete, so that with appropriate nonlinear amplification a simulation of the spread of excitation as a function of sound stimulus level can be approximated. On the other hand, excitation must not be too discrete, or effective higher level stimulation cannot be effected at acceptable current levels. The bipolar electrode elements described above would allow for operation of a simulation model with about a 15-20 dB dynamic range. This range is clearly adequate for fine grained control of the spread of excitation as a function of sound intensity, with appropriate amplification. As recorded below, required highest stimulus levels are well below what are judged to be "safe" upper limits of intracochlear electrical stimulation with these electrodes.

Electrode Excitation Patterns and Intracochlear Impedances

From consideration of electrode mapping studies conducted in cochleas of deaf animals with large regions with few or no surviving dendrites compared with electrode mapping studies conducted in cochleas in deaf animals in which most dendrites have survived the deafness pathology, it is evident that (as concluded earlier on the basis of strength-duration curves) it is myelinated nerve that is excited at threshold, and that the primary determinant of response threshold is the distance from exciting electrodes to nearest surviving myelinated structures. In cats with few or no dendrites, threshold for electrical stimulation is lowest directly over Rosenthal's canal, where a small percentage of ganglion cells still survive. In cats with many dendrites, threshold is low all across the bony spiral lamina. Thresholds are elevated over the organ of Corti itself. In any preparation, thresholds increase rapidly as electrodes are moved into the scala, i.e., away from its upper surfaces. These results are all consistent with the view that the bone of the spiral lamina provides little impedance barrier to electrical stimulation. This might be a consequence of observed openings intercommunicating between the channels through which the nerve is passing and the scala tympani and/or a simple consequence of a low resistivity of spiral lamina bone to these relatively brief (100 μsec/phase) electrical stimuli. Whatever the explanation, excitation patterns can be approximated by simple equipotential field models for stimulation with bipolar electrodes in a homogeneous medium. In a practical sense, then, there is no need to develop complex models of the impedance structure of the cochlea in order to approximate the excitation maps generated by different intracochlear electrodes.

Progress in Studies Designed to Evaluate Safety of Implantation and Stimulation

Can these multielectrode arrays be safely implanted? Can they be stimulated at levels of I required for operation of these devices? The UCSF cochlear implant research group has been investigating the answers to those questions in experiments conducted over several years (Schindler & Merzenich, 1974; Schindler, et al., 1977; Merzenich, et al., 1978). Among other results, these studies have revealed: 1) Long intracochlear arrays have been implanted into the scala tympani for periods of many months to several years in prior-normal or neomycin deafened cats without these arrays inducing significant loss of auditory nerve fibers, except in the extreme cochlear base. Surgical damage of the bony cochlea leads to new bone formation, and can result in restricted destruction of auditory nerve fibers. Any surgically induced perforation of the basilar membrane results in nerve fiber loss in the region of the perforation. Occasionally observed surgical trauma never resulted in total destruction of auditory nerve fibers. Testing in human cadaver material suggests that long (22-23 mm) intracochlear arrays can probably be implanted in human temporal bones with an acceptably low probability of surgical trauma. 2) Damage has been induced with long term, heavy electrical stimulation at current levels of about 4 mA and higher. With very heavy stimulation, bone growth is induced within the cochlea. Stimulation levels at which damage is induced are well above levels required for acceptable operation of these devices (about 1.5-2.0 mA). However, all hazards of high-rate multichannel stimulation have not been thoroughly investigated. For example, there are undoubtedly practical limits on the stimulus rates that can be employed in such devices (because of problems of heat dissipation), even at relatively low current levels.

Summary

These studies have revealed, to this time, many of the required features of reliable discretely exciting elements of multielectrode arrays. They have been discouraging, with respect to the application of "monopolar" or "common-ground" electrode arrays. With such electrodes, discrete excitation of restricted sectors of the auditory nerve array has not been effected. However, with closely spaced bipolar electrodes arrayed longitudinally or crossing the "dendrites" of the cochlea at an angle, very predictable and acceptably discrete excitation has been achieved. To effect discrete excitation with bipolar electrodes at low current levels, interelectrode separation must be small (0.5-1.5 mm) and the electrode contacts must necessarily be mounted on a carrier to assure that they are positioned near the upper surface of the scala. Surviving ganglion cells in dendriteless regions of pathological cochleas can be effectively (and discretely) excited, and elements of electrode arrays should be positioned to assure that such surviving ganglion cells are excited at relatively low current levels. The closest myelinated nerves or ganglion soma appear to be excited at threshold.

Implantation with long multielectrode arrays into the scala tympani does not itself necessarily lead to further destruction of auditory nerve fibers. On the other hand, there are several clearly defined surgical hazards of intracochlear implantation of these electrodes. Drilling or fracture of bone can result in new bone formation that can compromise electrode performance. This is of special concern because any charge assymetry in electrical stimulation will accelerate new bone formation. Similarly, damage of the fragile reticular lamina of the organ of Corti will lead to further nerve loss in the region of damage. (Surprisingly, tests in cadaver material of long arrays that have been designed for implantation 22-23 mm into the scala tympani in man have revealed that these models of prosthesis electrodes designed to effect multichannel stimulation appropriate for re-establishing a significant level of speech discrimination can be safely implanted in man.) Finally, stimulation-induced damage is a major consideration to the application of these devices. While studies on stimulus-induced damage are still incomplete, it now appears that damage is incurred only at stimulus levels well above those required for practical operation of multichannel electrical stimulation prosthetic devices. On the basis of some of these studies, 8-channel bipolar electrode arrays have been fabricated and have been implanted in two profoundly deaf patients. These patients are now the subject of intensive testing by the UCSF cochlear implant research group.

Acknowledgments

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