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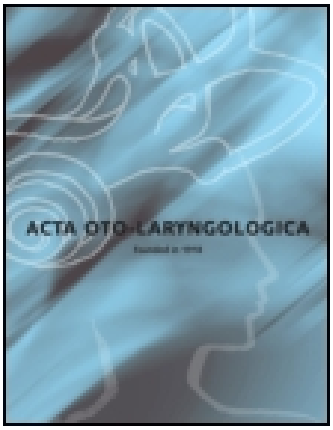

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SOME CONSIDERATIONS OF MULTICHANNEL ELECTRICAL STIMULATION OF THE AUDITORY NERVE IN THE PROFOUNDLY DEAF; INTERFACING ELECTRODE ARRAYS WITH THE AUDITORY NERVE ARRAY

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The problems inherent in development of multichannel electrical stimulation prosthetic devices with potential application to profoundly deaf subjects have been summarized, collectively, by a number of scientists who have considered overall developmental strategy in the framework of basic cochlear anatomy and pathology, cochlear physiology and the speech sciences; within the framework of clinical application; and within the framework of feasible engineering (e.g., see Simmons, 1969; Kiang, 1975; Kiang & Moxon, 1972; Merzenich, 1975; Schindler et al., 1977; Black, 1978). Obvious requirements for such devices include: (*a*) Electrodes must excite the auditory nerve in an appropriate way. (Only some of the characteristics of what constitutes an "appropriate way" have been resolved.) (*b*) Implanted devices and surgical implantation procedures must be acceptably safe; they must not lead to significant further destruction of the auditory nerve array. (*c*) Electrical stimulation at required current levels must be safe, and nondestructive *re* the auditory nerve array. (*d*) Appropriate "optimal" coding of sound must be defined for both speech processing and nerve stimulation stages of implanted devices. (*e*) Implantable electrodes and electrode driving hardware and external sound processing devices delivering "optimally coded" information must be fabricated. Surival characteristics of implantable devices must guarantee lifelong operation of the multielectrode array and acceptably long survival (and a convenient replacement strategy) for implanted telemetry hardware.

The UCSF cochlear implant research group has focused on problems inherent to safety and appropriate interfacing of electrodes with the auditory nerve array; on construction of multielectrode arrays and connectors; and on considerations of coding of stimuli by a multichannel electrical stimulation system. In this report: (*a*) our strategy in development of electrode arrays shall be outlined; (*b*) the potential application of simulation and nonsimulation electrical stimulation paradigms shall be considered; and (*c*) some factors relevant to safe electrode implantation and stimulation revealed by research by our group shall be summarized.

Development of a simulation model for electrical stimulation arrays

Elementary questions to be considered in development of an electrode array for a multichannel prosthesis include: What should multielectrode arrays stimulate? What nerve excitation model(s) should be employed? Should the response of the normal auditory nerve array be simulated? To what extent *can* it be simulated with multichannel electrical stimulation? What features of normal nerve response *cannot* be simulated? Can the features of the auditory nerve representation of speech necessary for its encoding in an intelligible

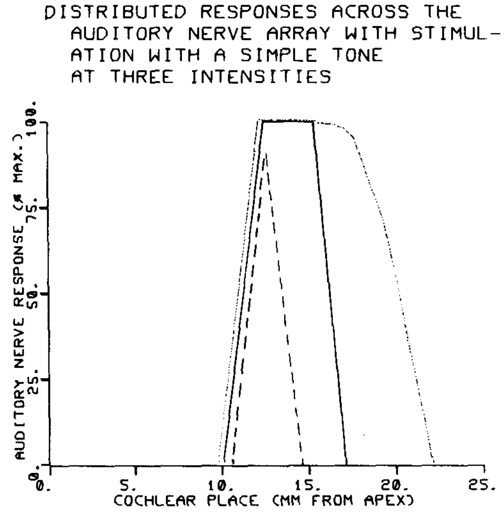

Fig. 1. Diagrammatic representation of excitation patterns generated by a tonal stimulus (about 2 KHz, in this example), at levels of about 40 dB SPL (– – –), 55 dB SPL (—) and 80 dB SPL (· · ·). Note that as stimulation levels are elevated about 50 dB, excitation spreads rapidly toward the cochlear base. At high stimulus levels, neurons over nearly half the cochlear are driven at or near highest possible discharge rates. (These curves are based on data derived in the nerve response mapping studies of Kim and colleagues.)

form be simulated? If not, what are the alternatives?

Most investigators have favored a simulation approach to auditory nerve stimulation. Some have appreciated that there are two stages to a simulation-based multichannel prosthesis (a speech processor and a nerve stimulator); others have not. In consideration of a simulation approach, the basic issues to be addressed, again, are: (1) What *can* and *cannot* be simulated? (2) What *must* be simulated? (3) How can the optimum simulation be achieved?

In a simulation model, it is obviously a facsimile of the temporal and spatial response patterns generated by sound *within the auditory nerve array* that is to be generated. The proper starting data for consideration of simulation devices, then, are spatio-temporal response maps, derived from unit population data (e.g., see Kiang, 1975), or defined directly by mapping response properties of neurons as a function of their cochlear position (e.g., Pfeiffer & Kim, 1975; Kim & Molnar, 1976; also see Tsuchitani, 1978). Such cochlear response mapping studies have revealed that spatial and temporal characteristics of excitation patterns are relatively simple, when derived for stimulation at levels below about 45 dB SPL. At these levels, excitation generated by different frequency components of sound are relatively discrete and distributed, and distortion product generation is not significant (see Fig. 1).

At levels above about 45 dB, very complexly overlapping excitation patterns are recorded with stimulation with complex sounds. This is a consequence of the fact that for any individual frequency component, excitation spreads rapidly toward the cochlear base (i.e., more and more basal fibers are excited), and because distortion products and powerfully interacting suppression phenomena complicate these patterns. Consideration of these response patterns at high stimulus levels are of major concern because of the implications they bear for necessary and sufficient features of the auditory code for complex signals (e.g., speech). But *they do not have to be simulated,* because speech is intelligible at stimulus levels of 40 or 50 dB SPL. The far simpler lower-level response characteristics constitute a more realizable model objective for simulation.

Spatial features of response in the normal cochlea: their encoding in a simulation-based prosthesis

Which of the spatial features of response for complex stimuli within such low to middle level excitation patterns can be simulated with electrical stimulation? What spatial features of responses cannot be readily simulated?

Some of the basic spatial features of response for sound stimuli delivered to a normal cochlea are illustrated in Figs. 1 and 2 (also see Kiang & Moxon, 1972; Kiang, 1975; Tsuchitani, 1978). Relevant features of the spatial aspects of the response within the auditory nerve array include: (*a*) At low stimulus levels (below about 45 dB), the nerve fibers in the center of the responding region discharge at relatively high rates; discharge rates fall rapidly both apical and basal to this central maximum. From stimulus levels of about 45–50 dB and above, neurons in the central responding region are saturated, i.e., their responses reach a limiting maximum. (*b*) The excitation pattern does not spread symmetrically as stimulus level is increased, i.e., the magnitude of response grows more rapidly toward the basal than toward the apical direction. As stimulus levels are elevated above 50–60 dB SPL, excitation spreads very rapidly across the auditory nerve array toward the cochlear base.

With appropriate bipolar stimulating electrodes, a crude simulation of this response can be effected. However, any *simple* simulation does not preserve three fundamental features of the normal response (Fig. 2). First (and least significantly), with electrical excitation, patterns are roughly symmetrically arrayed around discretely exciting electrodes. It is relatively difficult (and not practical) to simulate the normal assymetrical growth of the excitation pattern (even below 50 dB SPL) as a function of sound stimulus level (Fig. 2A). Second (and more importantly), it is difficult to simulate excitation as a function of position *within* the excited area. With electrical stimulation at a given stimulus level, nerve fibers are excited over a sharply delimited region in a nearly indistinguishable manner, i.e., discharges of neurons vary little across the excited region (Fig. 2B). Of course, with

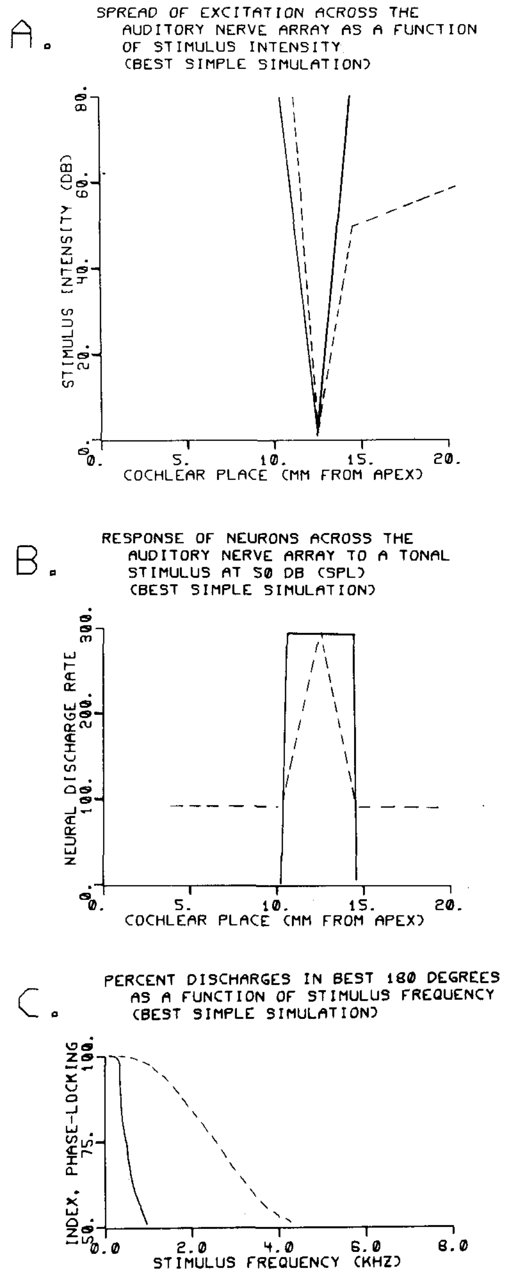

Fig. 2. Diagrammatic representation of the "best simple electrical simulation" (by discretely stimulating bipolar scala tympani electrodes) of three characteristics of the normal nerve array representation of simple sound stimuli. (A) Electrically generated simulation of neural tuning in response to stimulation with a simple tone. The normal response to a simple tone is illustrated in this and following drawings by a dashed line; the "best simple simulation" is represented by a solid line. The assymetrical growth in the response as a function of stimulus level (especially marked at higher sound stimulus levels) is not easily similated with electrical stimulation. (B) Electrically generated simulation of neural discharge rates in response to a simple tone, as a function of cochlear place. With electrical stimulation, nearly all excited neurons are excited at approximately the same discharge rates. (C) Simulation of the coding of the stimulus period at low stimulus frequencies. Curves represent an index of phase-locking of responses (% responses during best half cycle) devised for high (80 dB) SPL. (Based on studies of Anderson et al., 1971.)

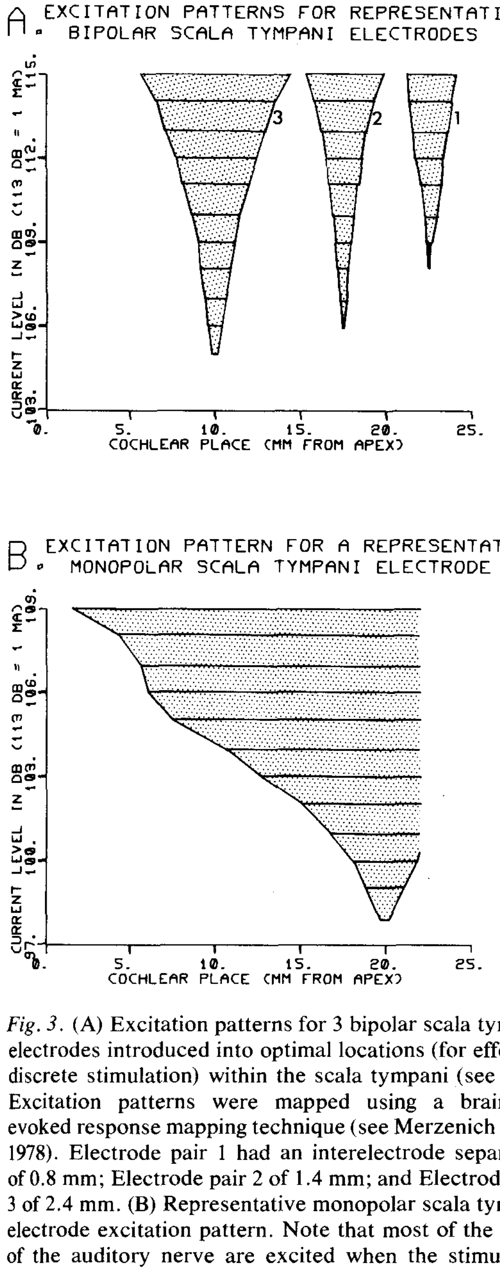

Fig. 3. (A) Excitation patterns for 3 bipolar scala tympani electrodes introduced into optimal locations (for effecting discrete stimulation) within the scala tympani (see text). Excitation patterns were mapped using a brainstem evoked response mapping technique (see Merzenich et al., 1978). Electrode pair 1 had an interelectrode separation of 0.8 mm; Electrode pair 2 of 1.4 mm; and Electrode pair 3 of 2.4 mm. (B) Representative monopolar scala tympani electrode excitation pattern. Note that most of the fibers of the auditory nerve are excited when the stimulus is elevated 10–12 dB above threshold.

normal sound stimulation, discharge rates in the center of the responsive region are high, while apically and basally they decline rapidly. (It is possible, at the present time, to only crudely simulate this internal spatial structure of normal excitation patterns.) Third, electrodes of limited numbers excite the auditory nerve array in fixed, invariant locations. Although excitation between the sites of electrodes can be effected by making use of field interactions with simultaneous stimulation of two or more electrodes (Merzenich & White, 1977; White, 1978), practical (i.e., highly predictable) control of neuronal excitation patterns by employing field interactions has not been achieved at this time. Again, at the present time, there are obvious limits on the numbers of stimulating electrodes of practical multielectrode arrays. (These limits are dictated by consideration of achieving adequate stimulus rates on individual channels; control of interactive phenomena; and hardware complexities; see Merzenich & White, 1977.)

Simulation of temporal aspects of response of the normal auditory nerve array

The temporal discharge characteristics of auditory nerve fibers vary systematically as a function of location across the auditory nerve array. Thus: (*a*) At low and mid-range stimulus frequencies (for neurons excited at those frequencies throughout the cochlea), there is a temporally coded representation of the stimulus period (see, e.g., Rose et al., 1967). This representation of stimulus phase is gradually degraded at successively higher stimulus frequencies above about 1 KHz (see Rose et al., 1967; Anderson et al., 1971). (*b*) For stimulation at any given frequency, there is a systematic (and in experimental animals, well defined) phase shift in the temporal representation of a given sound stimulus as a function of position across the auditory nerve array (consequent from mechanical travel time delays; e.g., see Bekesy, 1960; Kiang et al., 1965; Anderson et al., 1971).

The phase shift *between* channels due to travel time delays can be easily simulated. Phase shifts *within* the excitation patterns of individual channels cannot be simulated. It is possible to generate a reasonable facsimile of the normal representation of stimulus period only across the lowest ranges of frequency (below 400–500 KHz) (Fig. 2C). Auditory nerve stimulation studies (as well as nerve stimulation studies in general) indicate that some phase-locking of responses can be effected at stimulus rates up to perhaps 1 000 pps, but that the response is temporally degraded (when compared to normal) over much of this range (Moxon, 1971; Merzenich et al., 1974). No representation of cycle phase or period has been achieved at higher stimulus frequencies. Moreover, accurate simulation at very low frequencies requires a temporal distribution over the time course of the stimulus cycle that is difficult to duplicate with pulsatile electrical stimuli (see Fig. 2). (We know that these differences in temporal ordering of discharges are important. When a crude simulation of the normal excitation pattern is effected, a subject reports that the evoked sensation has markedly less timbre than the sensation evoked by a pulse train at the same rate.)

Simulation of non-linear interactive phenomena

With introduction of complex sound stimuli, two kinds of powerful interactive phenomena are recorded in the normal ear, i.e., two-tone suppression effects and combination tone generation. Given a fixed multielectrode array, both phenomena could be crudely modeled (given the same kinds of fundamental limitations in their detailed representation as apply for generation of simple responses). It is uncertain (and subject to psychophysical test) what might be gained by their inclusion in an operational simulation model.

What electrode arrays are most appropriate for producing a facsimile of normal sound-evoked nerve excitation?

A variety of electrodes have been tested, to determine to what extent spatially and temporally distributed responses within the auditory nerve array can actually be simulated with multichannel electrode arrays, and to determine how acceptably discrete excitation can be effected. Most attention has been paid to study of scala tympani electrodes, with which spatial dimensions of excitation patterns can be simulated.

These studies (see Merzenich & White, 1977; Schindler et al., 1977; White, 1978; Merzenich et al., 1978) have revealed that the most suitable stimulating elements of multielectrode arrays (tested to this time) are bipolar electrodes with the following characteristics: (*a*) Electrode contact surfaces are optimally oriented longitudinally (normal to the axis of fibers within the auditory nerve fiber array) along the bony spiral lamina, or at an angle transversely crossing a significant sector of the nerve array within the body spiral lamina. When dendrites are absent (e.g., in a very heavily damaged pathological cochlea), the "optimum" location for stimulation is with longitudinally arrayed electrodes positioned directly over the line of the spiral ganglion in the scala tympani. (With such electrodes, very discrete excitation of surviving ganglion cells can be realized.) (*b*) Acceptably discrete and acceptably low current level stimulation can be achieved with optimally oriented bipolar electrodes with interelectrode separations of about 0.7 to about 1.5 mm (measured from the centers of the two contact surfaces; see Fig. 3 A). The rate of spread of excitation as a function of current level is a simple function of interelectrode separation of bipolar electrode surfaces. (*c*) To achieve the most discrete stimulation, electrode contacts must be positioned on the surface of the bonyspiral lamina, i.e., discreteness of excitation is degraded as the bipolar pair is moved away from this surface into the scala, or is moved toward the extreme outer or inner margins of the upper surface of the scala. Mapping data are consistent with the conclusion (a first approximation) that *the geographically nearest myelinated nerve (or ganglion cell soma) is excited at threshold.* (*d*) When constant current stimuli are applied to these closely spaced and discretely exciting electrodes, excitation patterns are degraded little as contact surface area is increased, within limits. For example, acceptably discrete excitation patterns are generated without significant elevation of threshold with appropriately located electrode contact balls up to about 0.3–0.4 mm in diameter.

Acceptably discrete excitation has not been achievable with a variety of monopolar electrodes, or with electrodes employing common grounding schemes. It should be noted that it is, indeed, possible to achieve excitation of a restricted sector of the auditory nerve near threshold with such electrodes (see Meikle et al., 1978 and Fig. 3 B); however, the rapid spread of excitation across the nerve array as current level is increased makes it difficult to effect discrete multichannel excitation with such an electrode array (see Merzenich & White, 1978).

Safety of implantation of and stimulation with these scala tympani multielectrode arrays

Can arrays that can effect true multichannel stimulation of the auditory nerve array be safely implanted 20–25 mm into the scala tympani in man? Will stimulation with such electrodes at required current levels lead to any direct stimulus-induced damage of the cochlea? Can such electrodes be driven at current levels at which no irreversible electrochemical reactions occur at the electrode (platinum) metal surface? These questions are fundamental to application of this class (or any other type) of scala tympani electrodes.

An extensive study of the cochleas of implanted cats in which electrodes mounted in silastic carriers that fill the scala (insuring the approximation of electrode contact surfaces to the upper surfaces of the scala) has revealed that their implantation, if implanted nontraumatically, leads to no further destruction of auditory nerve fibers (see Schindler & Merzenich, 1974; Schindler et al., 1977). Specially designed human scala tympani multielectrode arrays have been fabricated that can be repeatedly implanted in cadaver specimens, apparently without inducing damage to cochlear structures.

Electrical stimulation at high levels can induce bone growth in the cochlea, as well as cause direct destruction of auditory nerve fibers. We are not yet certain as to whether or not any such damage or new bone formation can, under any circumstances, be induced with very long term stimulation at the top of the range required for application of this kind of device. (This question is being intensively investigated in our laboratory.)

Ideally, all applied stimulation would be effected at stimulus levels below those at which there is irreversible loss of free platinum from the electrode surface, with highest stimulus levels allowing for excitation of a reasonably broad sector of the nerve array (i.e., operationally, establishment of a workable dynamic range of loudness). This is probably possible with scala tympani electrodes with reasonable surface areas (e.g., 200–300 μ balls), with use of brief (100–200 μsec/phase) biphasic pulses (see Brummer & Turner, 1977; Spelman et al., 1978).

Summary of conclusions; what are the alternatives to a simulation model if it doesn't work?

With simple bipolar electrode arrays, it is possible to generate a crude simulation of the normal auditory nerve response with multichannel electrical stimulation. However, some basic spatial and temporal characteristics of response can be only poorly simulated. Any of several of these (e.g., inability to simulate the internal fine grain differences in discharge rates as a function of position across the nerve array, or inability to accurately simulate the temporally coded representation of stimulus period to stimulus rates of several thousand Hz) might seriously limit the usefulness of the simulation model. If this is, indeed, the case, what are the alternatives? It must be recognized that with more sophisticated multielectrode arrays, it is likely that a more detailed spatial simulation could in fact be generated (see Kiang and Eddington, this volume). Temporal coding limitations are more serious, however, and may not be possible to overcome. Perhaps more hopefully, given time and success in the development of multichannel electrodes, there are countless possible non-simulation models that might be pursued. In our own research, basic psychophysical experiments are being conducted that are designed to reveal how aspects of speech signals critical to intelligibility might be least equivocally coded across implanted multielectrode arrays. In this basic, non-simulation approach, these elemental components of speech sounds are then mapped across the multielectrode (and hence the auditory nerve) array (see White, 1978).

Recognizing the advantages of potential speech recognition capabilities in rehabilitation of post-lingually deaf patients, simulation models should continue to be vigorously pursued. However, multichannel electrical stimulation invariably and unavoidably results in patterned excitation of the auditory nerve that is very different from the consequences of excitation of the normal ear with sound stimuli. It is thus very possible that a non-simulation speech processor-nerve stimulator may ultimately result in higher levels of speech discrimination for implanted patients.

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