THE MULTICHANNEL COCHLEAR PROSTHESIS: CHANNEL INTERACTIONS

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ABSTRACT

Multichannel electrical stimulation of the cochlear nerve can generate complex interactions between the individual channels. Experiments with human subjects implanted with scala tympani electrode arrays indicate that the spatial "spread" of excitation is a strong function of the stimulus and of the type of electrode (ie. bipolar or monopolar electrode configurations).

INTRODUCTION

Multichannel cochlear prostheses are currently being investigated as aids in speech reception for the profoundly deaf. It is hoped that multichannel speech processors which divide the speech spectrum in contiguous bands may allow subjects to discriminate between the higher-frequency spectral components of speech. Multichannel stimulation may more accurately mimic normal auditory nerve excitation patterns. However, when two or more electrode channels are stimulated, strong interactions between the channels can occur. In this report, we will describe a strategy by which the nature and the extent of interchannel interactions can be measured and then we will describe the factors important in determining the extent of these interchannel interactions.

One type of interchannel interaction can occur when two or more channels are stimulated at precisely the same time. This type of interaction is described as a "simultaneous interaction" or as an "electric field interaction" because it may be the result of electric field summation and cancellation within the volume conducting tissues of the cochlea. When the stimulus polarity of one of two stimulated channels is changed, the pattern of neural activity can be significantly altered (1-3). Psychophysical experiments (4,5,8) indicate that behavioral responses (eg loudness and threshold measures) are significantly affected by reversing the stimulus polarity of one of two simultaneously-stimulated channels.

METHODS

At the University of California, San Francisco a small number of profoundly deaf subjects have been implanted with scala tympani intracochlear electrode arrays in an effort to partially restore their ability to understand speech. Each subject became deaf after acquiring the English language. A comprehensive set of speech perception and basic psychophysical experiments were conducted over the experimental period. In one set of speech reception experiments, a selected set of speech processors were evaluated to determine which processor would be most useful for the subject.

Data from our most recent subject is reported in this paper. He is 68 years old and had a gradual onset of hearing loss due to otosclerosis until he became profoundly deaf about 15 years ago.

Prior to implantation, subjects exhibited greater than 110 dB loss across the 100 Hz to 8 KHz frequency range (subjects were tested at octave intervals). Each of the subjects was unable to utilize high-power hearing-aids in standard speech discrimination tests. A thorough psychological evaluation was conducted to estimate how the subjects would respond to the consequences of the implantation. The subjects were selected for participation in this experimental study on the basis of their willingness and ability to participate in intensive psychophysical studies.

Subjects were implanted with scala tympani intracochlear electrode arrays of sixteen wires. The electrode array and the implantation procedure are described in detail by Loeb et al (6). The apical-most electrode was inserted approximately 21 to 26 mm into the scala. Each electrode contact was mushroom shaped in order to increase its surface area. The eight bipolar electrode pairs were spaced at 2 mm intervals along the Silastic intracochlear insert. The inter-contact spacing between bipolar contacts was approximately 700 microns, center-to-center.

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The bipolar electrode pairs were oriented approximately radial (and slightly diagonal) to the axis of the cochlea. Numbering of electrodes begins at the apical-most part of the array and progresses basally, such that the apical-most bipolar pair is labeled "(1,2)" and the basal most bipolar pair is labeled "(15,16)". An odd-numbered electrode represents an electrode contact placed more towards the modiolus (lateral) than the even-numbered (medial) contacts. In the monopolar configuration, only one intracochlear electrode contact was stimulated and the "return" contact was an ear-clip located on the ear lobe nearest the implanted cochlea. With monopolar stimulation, the same numbering system is used; but only one number is displayed to indicate which intracochlear electrode contact was stimulated.

All stimuli were delivered directly to the subject's electrode contacts via a percutaneous cable. This cable was connected through a set of relays to optically-isolated, constant-current stimulators (7). Each stimulator could generate a maximum of one milliamp peak of current. Stimuli were generated with a digital-to-analog converter at a sampling rate of 20 KHz. In the set of experiments described in this paper, only charge-balanced biphasic pulses were generated. During all tests, the subject could immediately terminate stimulation by disengaging a "master" switch which would immediately disconnect all electrodes from the stimulators. As an additional precaution, the computer program utilized a set of on-going "consistency checks" which verified that the system components were operating properly. If any one of these "consistency checks" proved invalid, stimulation immediately ceased.

Stimulus levels at threshold and equal-loudness levels were measured using a modified Bekesy tracking procedure using a minimum of 8 threshold reversals for each stimulus condition. For the threshold measurements, the subject pressed a button when he heard the stimulus and released the button when the stimulus was no longer audible. For suprathreshold level measurements, the subject was asked to press the button when the loudness went above the assigned loudness and to release the button when the loudness went below the assigned loudness. This method was relatively efficient and simple for the subjects to perform. Interstimulus interval was 0.6 sec. The average of the last 6 stimulus current minima and maxima was used as an estimate of the stimulus current required to maintain the specified loudness.

Interchannel interactions were measured by stimulating two channels with equal stimulus amplitudes. The stimulus amplitudes of both channels were varied together to determine the stimulus level required to obtain a given loudness. Then the polarity of one of the channels was reversed and the same measurement was made. Interchannel interactions were estimated by determining how much the stimulus amplitude (in uamp) had to be changed to maintain a constant loudness when the stimulus polarity of one of the two channels was reversed. The change in current was expressed as a ratio (in dB) of the stimulus currents (in uamp) for the two polarities. Measurements were made for a set of interchannel separations along the cochlea. Measurements were made for both bipolar and monopolar electrode configurations. In the experiments reported in this paper, polarity reversal did not significantly alter an individual channel's response. As a consequence, any changes in the two-channel responses can be attributed to "interactions" between the two channels. However, if an individual channel's response was significantly different for the two stimulus polarities, a modification of the above measurement technique could be used to compensate for the difference in the individual channel's response. The channel's stimulus amplitude should be changed when its polarity is reversed, so as to generate the same single-channel response for both polarities. To determine if and how much the stimulus amplitude should be changed, responses to single channel stimulation of both stimulus polarities were measured prior to the two-channel interaction experiment.

RESULTS

Figure 1 illustrates how the ratio (in dB) of the stimulus amplitudes (in uamp) varies with interchannel separation. In this set of measurements, only bipolar electrodes were used. Measurements were taken at three loudness levels: threshold, 50%, and 80% on a 0-100 loudness scale. Stimuli on each channel were trains of 200 usec biphasic pulses (100 usec/phase). The repetition rate was 100 pps and the trains were 300 msec in duration. By this measure, substantial interaction occurred over greater distances with the suprathreshold stimulus levels. This seems reasonable, since excitation might "spread" over larger portions of the nerve as loudness is increased.

In all interchannel interaction measurements reported here, the standard error was approximately 0.5 to 0.75 dB.

Identical measurements were made with monopolar stimulation in this subject. As with previously studied subjects (8), monopolar stimulation generated extremely widespread patterns of interaction. Current ratios of 4 to 5 dB at interchannel separations of 8 mm were common. At 2 mm interchannel separations, average current ratios of 14 dB were measured.

Figure 2 illustrates the results of an experiment similar to that illustrated in figure 1, the only difference being the repetition rate of the biphasic pulses. In figure 2, the repetition rate was 2000 pps. The results are very similar except for interactions at threshold. The data in figures 1 and 2 indicate that the extent or "spread" of interaction at

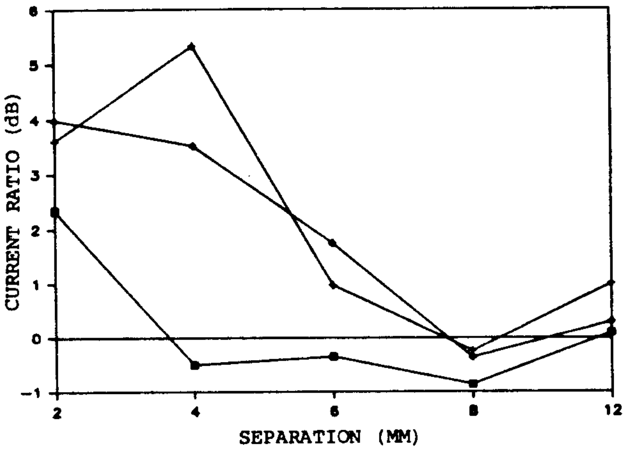

Figure 1. Interaction as a function of interchannel separation. Stimuli were 300 msec trains of 100 pps, 200 usec pulses. Squares represent measurements at threshold. Pluses represent measurements at 50% loudness. Diamonds represent measurements at 80% loudness on the 0-100% loudness scale.

near-threshold levels is highly dependent on the type of stimulus.

Additional interaction measurements have been made with other stimuli in order to better understand which stimulus features apparently affect the spread of excitation. In figure 3, interaction at threshold levels is plotted for two stimuli. Interaction for a single 200 usec pulse is compared to that for the 300 msec pulse train of 100 pps, 200 usec pulses. The two stimuli generate relatively restricted interaction patterns. Preliminary measurements at threshold indicate that single 6.4 msec pulses generate considerably more widespread interaction patterns than those illustrated in figure 3. This long pulse-width stimulus generated a somewhat smaller spread of interaction than the 300 msec train of 2000 pps, 200 usec pulses of figure 2.

The interchannel interaction data indicate that "longer effective duration" stimuli generate more widespread interaction at the lower loudness levels than do the "shorter effective duration" stimuli. A number of responses are a strong function of the "effective duration of the stimulus". Essentially, one type of response is generated with a single narrow-pulse-width pulse or with low-pulse-rate, narrow-pulse-width trains of any duration or with very-short-duration trains of high-pulse-rate, narrow-pulse-width stimuli. Another type of response is generated with single (or multiple) large-pulse-width pulses or with long-duration trains of high-pulse-rate stimuli. The major distinction between these two stimulus classes may be the "effective stimulus duration" (ie the duration over which the nerve membrane is depolarized). In the following discussion: (1) a single narrow-pulse-width

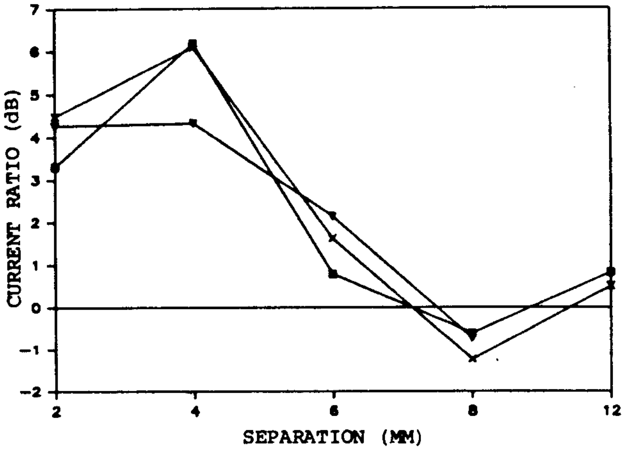

Figure 2. Interaction as a function of interchannel separation. Stimuli were 300 msec trains of 2000 pps, 200 usec pulses. X's represent measurements at threshold. Squares represent measurements at 50% loudness. Triangles represent measurements at 80% loudness on the 0-100% loudness scale.

pulse, (2) low-pulse-rate, narrow-pulse-width trains of any duration, and (3) very-short-duration trains of high-pulse-rate, narrow-pulse-width pulses will be referred to as "short-effective-duration" (SED) stimuli. In contrast, (1) single (or multiple) large-pulse-width pulses and (2) long-duration trains of high-pulse-rate stimuli will be considered "long-effective-duration" (LED) stimuli.

Related Data from Previous Experiments

A significant number of psychophysical measures (9) are a strong function of the "effective duration of the stimulus". This has been observed with both monopolar and bipolar stimulation. However, greater effects are

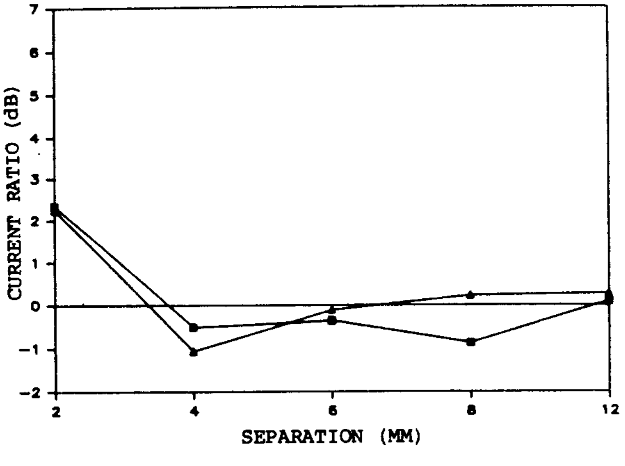

Figure 3. Interaction at threshold as a function of interchannel separation. Squares - stimulus was a 300 msec train of 100 pps, 200 usec pulses. Triangles - stimulus was a single 200 usec pulse.

generally observed with monopolar stimulation than with bipolar stimulation.

Dynamic ranges (9) are larger for LED stimuli (eg 15-35 dB) than for SED stimuli (eg 6-12 dB). The major differences in the loudness functions for the two classes of stimuli occur at the lower loudness levels. With LED stimuli, loudness more gradually increases with stimulus level at the lower loudness levels.

Intensity discrimination (9) is a very strong function of the "effective duration of the stimulus". At the lower loudness levels, intensity difference limens are much larger (eg 0.8 dB to 1.2 dB at a 10%-20% loudness level) for the LED stimuli than for the SED stimuli (eg .1 dB to .5 dB at a 10%-20% loudness level). At the higher loudnesses there is relatively little difference between the intensity difference limens across the two classes of stimuli.

A Model for the Observed Behavior

A relatively simple model has been simulated. The model results have been compared to the response features described above. The comparison has been encouraging. I will describe the components of the model that directly pertain to the response behavior described above. Other components of the model, which are necessary to accurately simulate other response features, are omitted.

In the model, neural activity is summed over time and space (ie across model neurons). For the present, we will assume a perfect summation across both time and space with the understanding that this may be a reasonable initial assumption only for a limited range of stimuli. Threshold current is defined as that current that is required to elicit a total of "Nt" spikes over all neurons and over the duration of the stimulus. The stimulus amplitude required to elicit an uncomfortably loud sensation is defined as that current that is required to elicit a total of "Nmax" spikes over all neurons and over the entire duration of the stimulus. Each neuron is modeled with the same sigmoid-shaped probability function that relates the probability of firing per unit time to the stimulus amplitude delivered to the neuron. The probability function approximates an integrated gaussian function (10). In the simulation work reported here, the probability of any given model neuron firing during a 20 msec interval was relatively low. In the model neuron's simplest form, the probability of firing linearly increases with the total duration over which the stimulus is excitatory. The stimulus amplitude delivered to each neuron is a function of the electrode type (eg monopolar or bipolar), the distance from the electrode to the initial site of excitation, and the magnitude of the current delivered to the electrodes. Data from Merzenich and White (1) were used to make initial estimates of the attenuation of the stimulus vs. the distance between the excitation site and the stimulating electrode. Although this model is described primarily in terms of a peripheral nerve excitation process, it may be just as easily described in terms of a more central mechanism incorporating the same key features.

Simulation results indicate that model neurons more distant from a stimulating electrode will play a more important role for longer duration stimuli than for shorter duration stimuli. To obtain a fixed number of neural firings, a lower stimulus amplitude is necessary when using longer duration stimuli. At the lower stimulus amplitude each model neuron exhibits a lower probability of firing per unit time. Because the stimulus duration is longer the total number of firings remains the same. _Interestingly, when the probability of firing per unit time of the neurons is reduced, the model neurons become more "alike"_. For any two model neurons, the ratio of their firing probabilities will tend towards unity as the probability of firing per unit time is decreased. This is simply due to the shape of the model neuron's probability function. This is a key feature of the model. Because the neurons become more similar at the lower probability levels, the neural activity is less spatially restricted for those stimuli that cause the neurons to operate at lower probabilities of firing per unit time.

In this model, dynamic range is smaller for SED stimuli than for LED stimuli because the shorter duration stimuli require that the model neurons operate on a "steeper" portion of the firing-probability-vs-stimulus-amplitude curve. Likewise for intensity discrimination, the shorter duration stimuli require the model neurons to operate on a "steeper" portion of the curve. Because the curve is steeper for SED stimuli, smaller intensity difference limens result. Again, the importance of the increasing steepness of the probability function becomes apparant.

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