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Single and Multichannel Cochlear Prostheses: Rationale, Strategies, and Potential

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Abstract

The development of auditory prostheses is moving into a new stage which should be characterized by the systematic comparison and optimization of the various single and multichannel systems now being developed. Both types of devices appear to be producing psychophysical and clinical results which are in agreement with well established biophysical models of electrical stimulation. Both types of devices are likely to find use in the general patient population, but clinical methods for selecting the appropriate device for a particular patient and systematically optimizing its results are still needed. Standardized tests of electrode performance, channel isolation, and parametric psychophysics must be agreed upon to permit comparative evaluations between devices and speech processing algorithms and across patients. The mechanisms for funding intensive clinical trials through the governments and manufacturers involved must be improved to assure efficient and orderly development of these high technology devices.

Introduction

Over the past three decades, the notion of restoring hearing to patients with hair cell deafness has progressed from the realm of science fiction to a commercially viable industry. This might be attributed to advances in electronic technology and in our understanding of the normal function and pathology of the auditory system, but it is largely the result of determined, even dogged, trial-and-error experimentation by a courageous group of pioneers scattered around the globe.

The question is no longer "will it work?" but rather "how well can it be made to work?" This is a fundamentally different kind of question, which calls for the meticulous approach of the scientist and the engineer rather than the derring-do of the inventor. However, complicating this inevitable transition of emphasis are the influences of commercial concerns, private philanthropies, government funding agencies, professional politics, and widespread publicity. Yet, in the long run, there must inevitably emerge some optimal design or, more likely, set of designs which provide optimal rehabilitation for the various types of patients and forms of deafness. This paper will explore the rationales behind the current devices and their results, much of which is admittedly post hoc, and will attempt to predict their potential clinical utility and outline strategies for their optimization.

Single Channel Devices

It is generally conceded that electrical stimulation of the auditory nerve via a single contact electrode has not and probably can not be expected to provide unaided understanding of speech (1). Stimulation through such an electrode will cause a spatially organized gradient of neural activity in a single population of auditory nerve fibers, which gradient may or may not be tonotopically organized depending on the location of the electrode. In all cases, the percepts have been described as complex sounds such as a buzz or clang rather than a pure tone, which tended to vary in loudness rather than pitch with the strength of the electrical stimulation. A modulation of pitch in the appropriate direction for changes of stimulation frequency (pulse or sinusoidal) over a range of about 50 to 300 cycles per second has been reported, but this is perhaps best described as a modulation around the inherent pitch of the stimulation site rather than a direct perception of a pitch equal to the actual frequency of the stimulus (4). The effect on perceived pitch of increasing stimulation frequencies above 300 Hz drops off rapidly, and most patients cannot even detect changes in stimulus frequency above 1000 Hz when loudness is equalized by adjusting stimulus amplitude.

All of this is entirely consistent with the classical biophysics of excitable membranes and the recruitment of a spatially distributed array of neurons by an electrical field with the temporospatial properties of a single channel auditory prosthesis (5). It also agrees well with the place-pitch theory's predictions of the CNS's interpretation of activity in the auditory nerve fiber population. In its pure form, this theory suggests that the intensity of sound of a given frequency is encoded in the rate of neural discharge from a spatially localized set of neurons which are mechanically tuned to the frequency of the acoustic stimulus. Like all other neurons, the auditory nerve fibers are limited to a maximum sustained firing rate of about 300 pps, further suggesting that little information about acoustic stimulus frequency can be obtained directly from neural firing rate, but leaving open the possibility that low frequency information such as that associated with timbre, voicing, and cadence may be so encoded. Because the mechanical tuning of the auditory neurons to higher frequencies is absent in prosthesis patients, the nervous system is unable to discriminate these frequencies of electrical stimulation (but see below for discussion of periodicity pitch).

From the extensive work on the minimal information content for understandable speech, it is clear that with even the most complete extraction of useful information by the CNS, there is simply not enough information present in the activity patterns induced by single channel electrical stimulation for speech to be understood (6, 15). However, this is not to say that single channel devices are not useful in the perception of speech, as well as in the performance of other acoustic tasks. At the simplest level, the mere awareness of the presence of sound and changes in its overall loudness over time are useful cues in attending to environmental sounds and voices and controlling voice loudness. Much speech information is contained in cadence and voicing, and the band of frequencies to 300 Hz also includes important first formant distinctions among vowels. These pieces of information are precisely what is lacking in lipreading, which provides much better information regarding high frequency aspects of speech such as consonants. The two together have been shown to be very effective (11, 13).

The ability to perceive changes in loudness and frequency within this restricted band of low frequency stimulation seems unrelated to the spatial selectivity or tonotopic locus of the electrical stimulation. Rather, it is the result of the electronic pre-processing that converts the acoustic waveform transduced by the microphone into the particular waveform of current passing through the electrodes and thus applied to the nerve fiber membranes. In particular, it seems to depend on the fidelity with which the acoustic signal can be compressed to the limited dynamic range of neural sensitivity to electrical stimulation and filtered to correct for the different sensitivities to different frequencies caused by the nerve fiber time constants (34). While simple in the abstract, these transformations are very tricky to control well in the context of normal conversational speech and typical ambient noise. Differences in the way they are accomplished probably account for as much of the differences between results with different patients and with various electrode designs as do differences inherent in the electrodes or the patients' pathology.

All of this would be consistent with the premise just stated, that the locus of single channel stimulation has little effect on the ultimate utility. The realization of this has sparked interest in extracochlear electrode sites such as the promontory and the round window (7). It has also led the intracochlear single channel implant to a more conservative, basally located contact. While there continues to be much controversy regarding the precise sensitivity of the basilar membrane and the spiral ganglion to mechanical and electrical trauma, there is general agreement that both are very delicate and subject to irrecoverable damage if abused (14, 20, 32). In the absence of any compelling reason to invade this space, it seems advisable to leave it alone, completely. This is particularly the case if the future implantation of a multichannel device is contemplated (21).

The optimization of the acoustic-to-electrical waveform transformation is just beginning to be systematicaly attacked for single channel implants. The delay is largely the result of the design of the House implant, which virtually eliminated any possibility of conducting meaningful parametric and psychophysical experiments. Its major advantage was and continues to be its extreme simplicity and attendant reliability, to which can now be added its clinical availability (through McGann Surgical Products Division of 3M Corp.). These are important attributes from the standpoint of a practitioner faced with the current needs of real patients, but they will surely pale in the light of designs which are both more conservative surgically and more flexible electrophysiologically. The single channel device now being developed by Biostim, Inc. proposes to combine several of the waveform transforms now under investigation into a single wear-home unit which telemetrically activates a much more versatile implanted receiver. This should greatly facilitate clinical optimization and evaluations of comparative efficacy.

The future for extracochlear single channel devices will depend somewhat on the ultimate achievements of intracochlear multichannel designs, but it is likely that a significant patient population will always be candidates for the simpler devices. Included in this group are likely to be all those whose auditory nervous system is so badly damaged or poorly developed that they cannot benefit from discrete channels of stimulation, as well as those who are too young or too handicapped in other ways to be properly fitted with complex systems. These considerations point up the importance of developing and implementing standard pre-operative estimates of the response of a given patient to electrical stimulation, which estimates can be correlated with the therapeutic results achieved with any of the different devices now under development (c.f. chapters on status of the auditory nerve in this volume). This promises to be a difficult and uncertain task, as data accumulate suggesting that present methods for promontory stimulation may produce high thresholds in normals (5) and patients with good prosthetic results (8). The use of dynamic range measurements as suggested by Smith and Simmons (29) and other more sophisticated tests will probably be required. However, it is only by amassing such a data base that we can sort out the advantages and disadvantages of each device vis-a-vis the various etiologies of deafness and functional needs of patients.

Multichannel Implants

Given a bandwidth limit of approximately 300 Hz in the information content that may be conveyed by any single channel of electrical stimulation, it is natural to suggest the addition of several parallel channels, each concerned with the transmission of information about a limited range of frequencies within the larger acoustic spectrum necessary for speech intelligibility. Given this strategy, a communications engineer might outline a set of critical specifications, develop tests of channel performance, design a system that makes optmal use of the channel characteristics, and build and test a prototype. Let us examine the progress to date in the light of such a systematic approach.

Theoretical channel requirements

If the information conveyed via each channel is independent, non-overlapping, and linearly recombinable by the receiving system, there are several ways of calculating the necessary number of channels. If we consider a total bandwidth of 300-3000 Hz for human speech, then we need approximately ten channels of 300 Hz bandwidth each. However, speech contains much redundant information even within this limited band, and is quite intelligible when synthesized from 6 or 8 single frequency samples within this spectrum (via frequency channel vocoder (6). If the frequency of a given channel can be swept (rather than fixed and amplitude modulated only), then only about four such channels are necessary, corresponding to the formant frequencies (plus high frequency unvoiced information) imbedded in the speech signal by the manner of its production (24).

Unfortunately, none of the three preconditions given above is likely to be found in the channels that are provided by even the best designed intracochlear electrode, and very little is known about the precise way in which these conditions are not satisfied or the implications of such failings for system design. The best that can be said is that the number of channels that must be provided will be at least four but should not exceed about 10. If useful results cannot be achieved within this range for at least one of the several possible schemes for dividing the speech band, it seems unlikely that further increases in channel number will salvage the situation. The geometry of the scala precludes achieving more channels with reasonable independence even if the technical problems could be overcome. Other less accessible and relatively unexplored loci such as auditory cortex might then have to be pursued.

This analysis is discouraging because it points up the enormity of the psychophysical task ahead of us as we sort through all these possible schemes and thoroughly explore all of the parameters within each one, often with only the vaguest a priori notions of how a given parameter can be expected to affect performance and interact with other parameters. On the other hand, one of the most technically demanding phases of the work is now more or less complete. Scala tympani electrode arrays with the requisite numbers of channels are now available in several different designs (2, 10, 16), and there are several schemes for percutaneous and transcutaneous transmission of multichannel signals from speech processors to electrodes (28, 30); (12). We can expect a rapid acceleration of the pace of psychophysical experimentation as investigators are able to select the hardware they need from a fairly comprehensive armamentarium.

Optimization of channel characteristics

With so much riding on the characteristics and independence of the various parallel channels, one might expect a great emphasis on models of the neural activation process and detailed animal experimentation to verify and quantify such models. However, this has been the exception rather than the rule, perhaps because most groups started with an electrode that was easily buildable rather than theoretically optimal in design. Only the groups at UCSF and, to a lesser extent, University of Washington in Seattle have probed in any depth into the temporospatial patterns of recruitment achieved with various current waveforms and electrode orientations and positions. This has produced an important set of benchmarks against which the performance of human implants can be measured (3, 19, 23, 26, 31, 33, 36). Fortunately, the results of both animal and human experimentation seem to organize themselves well into a model of the electrical excitability of the auditory nerve which is consistent with the biophysical and electrophysiological properties of this system (17). This facilitates the comparison of one device with another, but only when adequate descriptive and test data have been provided to structure the model.

Design and fabrication of implantable electrodes

The result of this systematic approach has been the selection by UCSF of a space filling electrode with radially oriented and carefully positioned pairs of independent, electrically isolated, bipolar electrodes. The theoretical advantages of such an arrangement are clear and the data suggest that any significant deviation from this optimal design produces measurable degradation of channel independence. However, this is also an extremely demanding design, for both implantable hardware and electronic signal processing (16). While such a near-optimal design makes a near-ideal research tool, future emphasis will have to be on identifying those aspects of the design that are truly critical and those that are just unnecessarily complicating fabrication. Conversely, some of the groups now employing electrode configurations that have compromised the achievable channel selectivity must be prepared to perform whatever experiments are necessary to demonstrate that their speech processing research is not being seriously compromised by hardware limitations.. It makes little sense to invest large amounts of time and money in sophisticated speech processors and multichannel telemetry equipment if all the electrodes are driving the same neural channels.

Psychophysical demonstration of channel separation

The selective activation of neurons by electrical stimulation is a matter of establishing highly localized and precisely oriented electric field gradients in the vicinity of the excitable target structures. While the optimal scala tympani electrode design is fairly well established, the actual performance achievable with such a device remains quite unpredictable. This is because of wide variability in the pathological lesions associated with various forms of deafness and even among subjects with ostensibly the same etiology (9). Further complicating this is the possibility of significant damage to the intact structures during surgical implantation and chronic electrical stimulation. The systematic application of channel interaction tests such as described elsewhere in this volume is absolutely critical to the interpretation of speech performance results (35, 37). We simply do not know how much channel overlap is tolerable or even desirable for various speech processing algorithms to be interpretable by the central nervous system. Thus, we cannot compare the results of different algorithms in different patients unless we can match them for degree of channel isolation over the dynamic ranges employed. While these tests are not unduly time consuming in practice, they are subtle in their design and successful implementation. A meaningful exchange of data regarding the effects of stimulus parameters seems unlikely until something akin to the MAC audiological function test (22) is carefully developed and widely disseminated.

Development of multichannel speech processors and telemetry

At first glance, the speech processor and the telemetry system seem like entirely separate pieces of hardware, each of which has its own specifications and methods of testing. Unfortunately, the compromises inherent in designing a practical multichannel telemetry system inevitably constrain the degrees of freedom of the signals that can be applied to the electrodes. The continuing uncertainty about such basic parameters as stimulus waveform and mono- vs. bipolar configuration has played havoc with attempts to develop generally useful systems based on digital multiplexing, although this technology looks promising in the long run. For those investigators who plan to explore speech processing at a basic level, it continues to seem wise to rely on either percutaneous connectors or multiple analog RF links, despite the surgical problems and cumbersome technologies involved in both.

The comparison of the speech processing algorithms employed by various groups continues to be plagued by our limited understanding of the ramifications of nonlinear devices such as dynamic compressors and clippers. Even investigators with solid backgrounds in signal theory omit crucial parameters from their descriptions of their equipment and experimental protocols. And for those who have not spent hours in front of speakers and oscilloscopes, even the most complete descriptions have little value. I would propose that we begin supplementing published descriptions with examples of the actual output waveforms resulting from some generally agreed upon set of test signals. Kiang and Moxon (15) used the test phrase "shoo cat" to generate clear graphical representations of the response of the auditory nerve fibers to a "real" input; something similar is needed to keep the discussion of speech processors at a level where all of the different specialists involved in their design and implementation can contribute.

Basic Physiology Questions

I cannot accept an invitation to wax philosophical about a neural prosthetic application without mentioning the opportunities for basic neurophysiological progress that are inherent in these unique excursions into the human CNS. Despite years of intensive neurophysiological experimentation in animals, the processes by which we derive even so basic an attribute of a sound as pitch remain obscure.

Most of the multichannel electrode designs and speech processor strategies are based on a Helmholtzian view of the normal encoding of pitch based on place of maximal activation along the basilar membrane. However, researchers involved in the normal neural encoding of speech sounds have, over the past decade, generally concluded that the place pitch cues are simply too poorly spatially resolved at the loudnesses encountered in normal speech (25). This suggests strongly that the auditory nervous system is regularly extracting information concerning formant freqencies from the phase-locked information contained in the normal activity of auditory nerve fibers subserving the 300-3000 Hz region of the basilar membrane.

The generally accepted mechanisms for extracting pitch from phase-locked discharges involve the neural equivalent of temporal autocorrelation to determine the fundamental period of frequencies up to 2 to 3 kHz. There has been a controversy in the psychophysical literature concerning certain predictions of this "periodicity pitch" theory and the predicted response of the auditory system to complex acoustic stimuli. However, as Whitfield (38) pointed out shortly after the first published results of intracochlear prostheses, the ability to directly electrically activate auditory nerve fibers eliminates much of the ambiguity of acoustic psychophysics. The finding that these subjects were insensitive to frequencies of stimulation above the single neural following frequency (300 pps) was troubling, indeed. The two simple explanations for this finding were that the neurons were not, in fact, phase-locked to the higher frequencies of electrical stimuli, and that the stimuli were being applied to relatively basally located neurons which normally convey nonphase-locked activity from high frequency acoustic stimuli. Both of these explanations have recently been discounted. We have directly demonstrated single neuron phase-locking in the cat anteroventral cochlear nucleus (AVCN) to scala tympani electrical stimulation similar to that employed in cochlear prostheses and for frequencies over 3 kHz (36). Furthermore, bipolar electrodes capable of well-localized stimulation have now been advanced well into the second cochlear turn of patients with apparently good auditory nerve survival. Electrical stimulation has been applied there at frequencies which should have caused phase-locking similar to that normally conveyed by these neurons when acoustically activated. However, these patients continue to be unable to detect changes in stimulation frequency over about 500 Hz.

We have been considering other mechanisms whereby the phase-locked information in both normally and prosthetically activated neurons might be processed and interpreted by the CNS (18). This work is still in its infancy, but it will certainly depend heavily on the special types of psychophysical experiments that can be performed on auditory prosthesis patients. Conversely, it is hoped that an improved understanding of the nonplace-pitch mechanisms of the CNS will advance the design of implantable electrodes and speech processors. It is also possible that these mechanisms might account for the ability of the so-called "miracle" patients who appear to be able to extract more speech information from single channel stimulation than would seem to be possible from their psychophysical responses to simple waveforms.

Conclusions

The development of auditory prostheses is entering a new phase, which will, at its best, be characterized by the development and application of new and rigorous analytical techniques. Much as medicine in general moved into the post-Flexnerian era and abandoned testimonials in favor of the scientific method, so must we, too, move from anecdotes to analysis. Unfortunately, this is going to be even more expensive than our progress to date, since it will involve large numbers of patients, practitioners, and researchers, plus complex test equipment which is not commercially available.

In that context, the interest of large commercial ventures in these devices offers a mixed blessing. On the one hand, they offer a much needed source of capital in these hard times. On the other, their perspectives must be limited by their objective of developing timely and profitable products in a competitive market. It seems unlikely that private enterprise can provide either the amount of money or the oversight and discipline needed to insure steady progress. What can and should emerge from the growing commercial activity, however, is a strong sense of the importance of such progress to avoiding a situation in which truly vast amounts of money are spent in the widespread clinical application of suboptimal devices.

This leaves the various national governments to provide and, more importantly, to coordinate research funding. Unfortunately, governments generally have little experience with such big science undertakings in the biological and, particularly, in the neurological sciences. In the U.S.A., the random submissions of proposals for individual research grants, program-project grants, and clinical centers are parsed almost as randomly to study sections with broad basic science and/or clinical mandates. These hard-pressed groups are already having to make nearly arbitrary funding judgments about traditional small-scale research projects involving conventional technologies. They cannot be expected to cope well with the occasional large scale, high technology, applied research project when it is thrown into the same pile. The contract mechanism, under Dr. Hambrecht's Neuroprosthesis Program at NIH, has been instrumental in coordinating technical development of hardware, but this is probably too restrictive in structure for the highly multidisciplinary work outlined above. One solution may be technologically oriented study sections with ad hoc biological and clinical scientists to assure that proposals are realistic. While there appears to be recent political support for such an applied science emphasis, there is also a long-standing and not-wholly-unfounded reluctance on the part of the biological basic science community. The sort of long-term, multidisciplinary research outlined here will be very difficult to puruse until this situation is rectified.

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