Comparison of Normal Hearing to the Auditory Percepts Evoked by Cochlear Implants

Robert V. Shannon
Coleman Laboratory, HSE-863
University of California, San Francisco

Cochlear implants are now in common use to provide some auditory sensation to the profoundly deaf. This paper provides a review of the variety of implant devices currently available, their relative merits and limitations, and compares the perceptions evoked by these devices with persons of normal and impaired hearing. Psychophysical results will be described which allow a comparison of perceptual function in persons with cochlear implants to that of those with normal hearing. Temporal processing appears to be similar for normal hearing and electrical stimulation. This implies that the major temporal aspects of auditory perception are not determined in the cochlea, but more centrally in the system. Frequency resolution, however, is completely absent with electrical stimulation. Multichannel implants are being developed to stimulate different regions in the cochlea in an attempt to mimic the normal tonotopic frequency analysis. Cochlear implant stimulators should be customized to fit the patient in a way that will maximize the preservation of the relevant temporal sequences in speech.

The use of electrical stimulation to create auditory sensation in deaf patients has been under intensive study since the first demonstrations by Djourno and Eyries (1957). In the last few years, cochlear implants have been used in large clinical populations: over 350 patients have been implanted in the U.S. by House and co-investigators (e.g., House, 1976; Edgerton, Doyle, Brimacombe, Danley, & Fretz, 1983) and more than 58 patients have been implanted in France by Chouard, Fugain, Meyer, and Lacome (1983). In addition to these clinical trials, several groups around the world are working with a small number of patients and studying each patient intensively (Clark, Shepherd, Patrick, Black, & Tong, 1983; Eddington, Dobelle, Brackman, Mladejovsky, & Parkin, 1978; Fourcin, Douek, Moore, Rosen,

Robert V. Shannon, Ph.D. is an Assistant Professor in Residence, Department of Otolaryngology, University of California at San Francisco, San Francisco, California.

Walliker, Howard, Abberton, & Frampton, 1983; Simmons, 1983; Dillier, Spillman, & Guntensperger, 1983; Hochmair & Hochmair-Desoyer, 1981; Hochmair & Hochmair-Desoyer, 1983; Shannon, 1983, in press). As more knowledge is gained about the factors that determine implant performance, cochlear implants will become common prosthetic devices.

The early cochlear implants were single-channel devices. They stimulated the cochlea by applying current to a single wire in the scala tympani. With only one channel, these devices could only convey a single stream of information to the auditory nerve. Most of the early devices were monopolar (return current path external to the cochlea) which produced a broad distribution of current. Probably the entire surviving VIII nerve was stimulated with this single stream of information. These devices gave patients some help in environmental awareness, lip reading, and in modulation of their own voice. However, total speech recognition was not achieved.

To provide patients with more information, multichannel implants were designed to deliver electrical stimulation to different populations of neurons. Typically, a multiwire electrode is inserted into the scala tympani with the electrodes extending longitudinally along the cochlea. If each electrode could stimulate different groups of the tonotopically-arrayed nerves it would be possible to present several streams of information and attempt could be made to recreate some of the intricate pattern of nerve responses of the normal cochlea. It was hoped that, if the important aspects of these patterns could be reconstructed, dramatic improvements in speech recognition would result. Unfortunately, the results with multichannel stimulation to date have been disappointing. Most multichannel devices show little or no improvement over single channel implants.

In this paper, the different implant devices currently available or under development are listed, the biomedical considerations common to all devices are discussed, the basic psychophysical results common to all devices are described, and the implications of these results to future implant design are mentioned.

CURRENTLY AVAILABLE DEVICES

There are currently nine centers around the world doing active research on cochlear implants. In addition, there are several commercial interests and dozens of otologists engaged in implants who are affiliated with one or more of these groups. The specific characteristics of these devices are listed in Table 1. Most devices are inserted into the scala tympani, although recently more attention has been given to extra-cochlear placements. Most current devices process sound via a vocoder analysis, termed "analog-filtered" in Table 1. To date, coding significant features of speech has not been more effective than this simple vocoder approach.

All implants consist of four basic parts: the electrode, a surgical discon-

Table 1

Summary of Device Placement and Data Transmission Schemes for Cochlear Implant Research Groups

Group Location	Electrode		Data Transmission		Number of Patients
	Position	Number of Contacts	Pulse or Analog	Feature Extraction or Filtered	
Australia	Scala Tympani	20	Pulse	Feature	6
London	Promontory	1	Analog	Feature	4
Los Angeles	Scala Tympani	1	Analog	Filtered	350
Paris	Scala Tympani	14	Pulse	Filtered	58
Salt Lake City	Scala Tympani	6	Analog	Filtered	3
San Francisco	Scala Tympani	16	Analog	Filtered	4
Stanford	Scala Tympani	16	Pulse	Feature	2
	Modiolus	6	Pulse	Feature	2
Vienna	Scala Tympani	4-8	Analog	Filtered	13
	Promontory	1	Analog	Filtered	2
	Round Window	1	Analog	Filtered	4
Zurich	Round Window	1	Pulse	Feature	4

nect, a transcutaneous (or percutaneous) receiver, and the external stimulator device. The electrode is implanted in or near the cochlea. Electrodes contain single contact surfaces or as many as 20 contacts. The wires coming from the electrode either go directly to the implanted receiver coil or are coupled to the receiver via a surgical disconnect plug. This plug allows the receiver to be replaced or modified without disturbing the electrode(s) in the

cochlea. The transcutaneous receiver is typically a coil of wire serving as an antenna to receive the stimulating signals through the skin. Some receivers have electronics implanted with them, while others are passive antennas. The external stimulator device receives sound through a microphone, translates the acoustic signal into an electrical signal, and delivers it to the internal receiver. Some devices use electrical analog signals similar to the acoustic waveform, while others code the acoustic signal into a series of electrical pulses.

The most common single channel device is that used by the House Ear Institute and co-investigators. This device is a single wire which is inserted 6 mm into the scala tympani and is stimulated transcutaneously via a coil receiver implanted in the mastoid bone. This device is largely unchanged from the first implant by House in 1971. However, even though this device is technically unsophisticated, patients with this implant perform nearly as well as the average patient with current multichannel devices.

Another approach to single channel stimulation has been to position the electrode external to the cochlea. The group in London (Fourcin et al., 1983) uses a single, removable electrode on the promontory. Other groups (Hochmair & Hochmair-Desoyer, 1983; Dillier et al., 1983) surgically implant a device similar to the House single channel device, but the electrode is fixed in the round window niche rather than inserted into the scala tympani. External electrodes have the advantage that they do not invade the cochlea and so avoid any long term damage that might be caused by the insertion of a foreign body into the cochlea. External electrodes can be removed and/or replaced more easily than intra-cochlear devices, allowing insertion of an intra-cochlear device at a later time. Extra-cochlear devices have the disadvantage that the electrode is further from the nerves and thus require higher current levels for normal operation. Preliminary data from patients with extra-cochlear devices indicate that speech recognition is similar to that achieved by intra-cochlear implant patients.

Most research has concentrated on the multichannel scala tympani electrode (Atlas, Herndon, Simmons, Dent, & White, 1983; Hochmair-Desoyer, Hochmair, & Burian, 1983; Loeb, Byers, Rebscher, Casey, Fong, Schindler, Gray, & Merzenich, 1983). The construction of the silastic carrier and the electrode contact surfaces are different between groups, but the basic designs are similar. All include multiple wires inserted through the round window that terminate in contact surfaces at different distances around the first turn of the cochlea. All groups except for the Salt Lake City group use a silastic mold to hold the wires and to maintain their relative positioning on insertion. The Salt Lake City group inserts individual wires to different depths through the round window (Eddington et al., 1978). All of these implants produce nearly equivalent performance. There is some indication that multichannel implants can produce better speech recognition than single channel devices (Eddington, 1983), but the improvement is small. At this point in time, mul-

tichannel stimulation has produced no dramatic advantage over single channel. However, optimism still runs high that new coding schemes will allow multichannel implant patients to achieve improved speech recognition.

BIOMEDICAL CONSIDERATIONS

Any implanted prosthetic device should be constructed of materials that are not toxic to the body and designed so that its insertion and use do not cause damage to remaining structures. All current cochlear implants are made of similar materials, which are all biocompatible. Several different strategies exist for the best electrode design and insertion method to minimize the possibility of trauma. At present, it appears that all methods allow trauma-free insertion.

Materials Biocompatibility

All current implants use electrodes made of platinum or an alloy of platinum and iridium. These are the "noble" metals and so are chemically very stable. Electrochemical tests (Brummer, Robblee, & Hambrecht, 1983) have shown that these electrodes do not give off toxic reaction products when stimulated in conditions that mimic those of cochlear implants. Most electrodes are insulated with Pyre-ML or Parylene-C, or both. These insulants are durable and bond well to the platinum surface. Insulation failure is not a problem with any current implant electrode assembly.

The receiver-connector portion of the implanted devices are positioned in a recess drilled into the mastoid bone. These packages are made of several different materials; some include electronic components sealed inside, while others do not. All except the Salt Lake City device and the Stanford device use an internal coil as an antenna to receive the signals for the cochlear electrode. Some of the devices are sealed in a titanium can, some in ceramic or glass packages, and others simply coat the internal parts in medical grade epoxy. While achieving a hermetic seal on these packages has been a technological problem, the devices, once successfully sealed, seem to have an acceptable lifetime without leaking. Attaining a hermetic seal is still a considerable problem. The Salt Lake City and Stanford groups avoid this problem by connecting the electrode wires directly to a percutaneous connector, which allows direct connection to all wires with no internal antenna or electronics. The San Francisco group uses this method for a three month period while performing perceptual tests on the patient. One problem with this approach for long term application is the possibility of infection invading the opening in the skin. However, infection has not been a problem for the Salt Lake City patients.

The receiver-connectors are fixed to the mastoid bone by methylmethacrylate, sutures, or screw-fit. All of these methods seem to hold the device securely in place and do not produce infection or foreign body rejection

reactions.

Insertion Trauma

When inserting any electrode into the scala tympani there is a possibility of damaging the delicate structures of the cochlea. Implant patients presumably have no remaining hair cells, but damage can occur in the spiral lamina or basilar membrane. Insertion trauma to these structures can cause degeneration of remaining nerves in the area of the damage, which could result in a degradation of the effectiveness of the prosthesis.

Most multichannel electrodes are housed in a silastic carrier. The entire assembly is inserted through the round window. Some of the electrodes are molded in the spiral shape of the cochlea. These must be straightened for insertion and then resume their coil shape on contact with the far wall of the cochlea. Others are molded in a straight array and require the force of insertion to bend the array around into the cochlea. Both of these methods appear to be satisfactory for avoiding insertion trauma.

One other consideration is the twisting of the electrode as it is inserted. For all devices except for the Australian device, rotation of the electrode could result in electrodes that are not properly positioned near the remaining neurons, and thus reduce the effectiveness of the implant. The San Francisco device has been designed (Loeb et al., 1983; O'Reilly, 1981) such that with normal rotation on insertion the electrodes all rotate into the proper location under the basilar membrane. The Australian electrode does not have this problem because their electrode contact surfaces are bands encircling the silastic carrier, and thus are rotationally symmetric.

Extra-cochlea devices do not have the same problems of insertion trauma as scala tympani electrodes. However, since they are positioned external to the cochlea their electrode contact surfaces are relatively distant from the neurons to be stimulated. This causes extra-cochlear devices to have high thresholds and poor specificity. At high levels of current any device can cause facial (VII) nerve stimulation and/or mild pain sensations. This may be a particular problem in high threshold extra-cochlear devices.

Stimulation Trauma

Damage can also occur to the remaining cochlear cells from electrical stimulation *per se* (Leake-Jones & Rebscher, 1983). Animal experiments have shown that the damage occurs as a function of the charge density at the electrode contact surface; i.e., the amount of charge delivered per square centimeter. Thus, it is desirable to have large electrode surface areas and minimum current levels. All devices use enlarged contact surfaces on each wire to maximize surface area. The minimum charge can be achieved by correct electrode positioning near the surviving neural elements, as discussed in the previous section. The accepted safe limit for charge density is $40\mu C/phase/cm^2$ (Walsh & Leake-Jones, 1982). All devices operate at lev-

els below this limit.

SUMMARY OF PSYCHOPHYSICAL RESULTS

The results of psychophysical tests on implant patients and in animal models have been presented elsewhere (Muller, 1981; Tong, Clark, Blamey, Busby, & Dowell, 1982; Shannon, 1983a, 1983b; Pfingst, Donaldson, Miller, & Spelman, 1979) and will only be summarized here. Experiments have been done to characterize the basic perceptual attributes evoked by cochlear stimulation and their physical determinants. Measurements have been made of the threshold and dynamic range as a function of frequency, growth of loudness, intensity discrimination, frequency discrimination, temporal integration, simultaneous and forward masking, tone decay and pitch. Table 2 presents four hypotheses based on the present results and lists experiments that support them. In general, measures of temporal processing were similar to normal, but there is no frequency analysis of the electrical signal.

Table 2

Major Hypotheses About Psychophysical Results
from Implant Patients and Supporting Evidence for Each

Hypothesis	Supporting Evidence
1. No frequency resolution	No frequency specific —simultaneous masking patterns —forward masking patterns —poor frequency discrimination above 300 Hz
2. Normal temporal processing	Gap detection 30ms near threshold 2ms at high level Forward masking time constant = 300ms Threshold integration time constant = 200ms Suprathreshold integration time constant = 50ms
3. Low frequency threshold levels are related to dendrite survival	Animal psychophysics and histology in same animal VIII nerve physiology with electrical stimulation
4. 300 Hz limit on temporal processing	No pitch change above 300 Hz Threshold function breaks at 300 Hz No "frequency" discrimination above 300 Hz

Figure 1 shows a schematic plot of typical threshold and uncomfortable loudness levels (ULL) as a function of frequency. The dynamic range is 30-40 dB at frequencies below 100 Hz and 15-25 dB for frequencies above 300 Hz. The rise in threshold from 100 Hz to 300 Hz is typically 20-30 dB. Experiments by Pfingst et al. (1979), Pfingst, Sutton, Miller, and Bohne

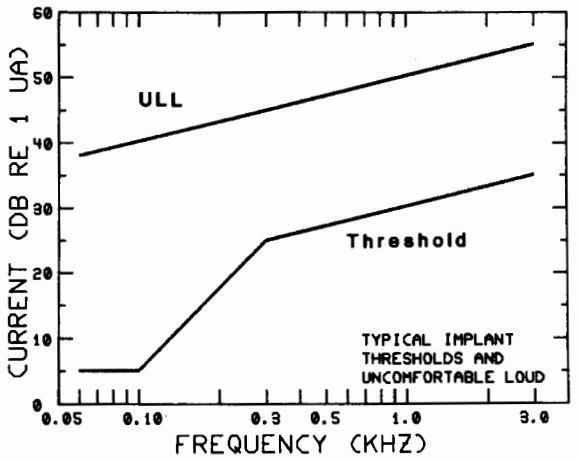

Figure 1. Schematic plot of typical threshold and uncomfortable loudness levels (ULL) for electrical stimulation versus frequency.

(1981), and Pfingst and Sutton (1983) with monkeys show that this difference is dependent on the degree of nerve survival in the region of the electrode. Most groups find the knee in the threshold curve at about 300 Hz but others have seen it as high as 1000 Hz. Many aspects of the perception of electrical stimulation change at 300 Hz: the threshold curve changes slope, the pitch of an electrical stimulus does not change above 300 Hz, the dynamic range is constant above 300 Hz, and little or no frequency discrimination is apparent above 300 Hz. It is possible that this frequency represents a limitation of electrical information due to biophysical properties of the nerve membranes (Guttman & Hachmeister, 1971). It appears that only the envelope of the stimulating waveform is the effective stimulus for frequencies above 300 Hz.

The loudness of an electrically evoked sensation is related by a power law to the stimulus current amplitude, similar to normals. However, the exponent for normals is .6, whereas for electrical stimulation the exponent is 2 to 3.5 depending on frequency. These values are similar to the exponent observed for electrical shocks delivered to the skin (Stevens, 1960). Linear amplitude compression is required in an implant stimulation device to preserve the loudness ratios within the dynamic range.

There does not appear to be any frequency selectivity for electrical stimulation. Muller (1981) presented simultaneous masking curves in implant patients. The electrical "masker" potentiated the response to the signal. A simultaneous masker actually *decreased* the threshold of a signal, and the decrease was the same magnitude for all signal frequencies. Shannon (1983) presented masking patterns for forward masking in implanted patients. A forward masker did produce an elevation in the signal thresh-

old, but again the amount of masking in dB was the same for all signal frequencies. Further, Shannon reported no frequency discrimination above 300 Hz, while others have reported measurable, but poor frequency DL's above 300 Hz. Any "frequency" discrimination below 300 Hz was probably due to temporal rate discrimination.

Several measures of temporal processing in cochlear implants have been reported and all show near-normal temporal integration. Threshold and supra-threshold measures of temporal integration show time constants of 200-300 msec and 50-100 msec respectively, both times similar to normals (Plomp & Bowman, 1959; Zwislocki, 1969). The just detectable gap duration was long near threshold (60 msec gap just detectable) and decreased to 1-2 msec for loud stimuli. Again these times are in the normal range for high frequency or broad-band stimuli.

Most implant patients have shown pronounced tone decay with electrical stimulation. A medium to loud sound can fade to inaudibility in less than one minute. No decay of sensation is observed if the stimulus is amplitude modulated at rates as low as 2 Hz. A similar phenomenon is observed in some sensorineural hearing loss patients.

The amount of masking produced following a masker (forward masking) as a function of the signal delay was measured as an indication of the recovery from the adaptation produced by the masker. The recovery times were similar to, or a little longer than, measures of forward masking in normals (Shannon, 1983).

Pitch measurements yielded a confusing pattern of results. Some investigators (Tong & Clark, 1983; Eddington et al., 1978; Hochmair & Hochmair-Desoyer, 1983) found that the pitch from stimulating different electrodes changed monotonically with cochlear position. Others (Shannon, 1983) found a nonmonotonic relation between pitch and cochlear position. Interpretation of the pitch data is hampered by our incomplete knowledge of how pitch is coded in the normal cochlea.

The pitch sensation evoked as a function of electrical frequency is quite different from that evoked by the acoustic frequency. The perceived pitch has been observed to increase dramatically as electrical frequency is increased from 100 to 300 Hz. One patient described this pitch range as "greater than four octaves". Above 300 Hz the pitch did not change with electrical frequency. Since there is no frequency analysis of the electrical signal this pitch sensation is probably due only to temporal rate. In normal hearing the pitch associated with temporal rate increases only up to rates of 300-500 Hz also (Burns & Viemeister, 1976).

The results just discussed apply to stimulation of a single electrode (or channel) at a time. Most multichannel implant strategies involve simultaneous stimulation of two or more channels. In order for multichannel implants to be a viable prosthesis these channels must be independent of each other. If all channels add electrically prior to stimulating the nerve

then the device is in fact a single channel stimulator from the vantage point of the nerve. Presumably, channel independence is achieved when each channel stimulates a unique group of neurons. It is important to measure the independence between channels in order to assess the viability of a multichannel prosthesis. Several methods have been proposed (Shannon, in press) to measure the amount of perceptual interference that results from stimulating two channels simultaneously. These results showed that some patients had extensive electrical interactions between different electrodes. This seriously limits the possibility of multichannel stimulation in these patients. It is not yet clear how channel interaction is related to patient etiology or device design.

IMPLICATIONS FOR SPEECH RECOGNITION

The comparison of psychophysical results in implant patients and normals indicates the role of cochlear processing in speech perception. Temporal processing appears to be similar in implant patients and normals. This implies that the mechanisms that determine temporal perception take place in the auditory pathway central to the cochlea. In addition, the temporal properties of the normal cochlea (e.g., travel time on basilar membrane, filter response time) are not the determining factors for psychophysical measures of temporal processing.

Any critical features of speech that are dependent on temporal processing should be preserved in cochlear implants. Implant patients report that the prosodic features of speech sound normal. They are also able to detect changes in the fundamental frequency of speech, allowing them to tell the difference between speakers, to discriminate voice from noise, and discriminate questions from statements (Owens, Kessler, & Raggio, 1983). Some patients can even discriminate vowel stimuli that differ only in their first formant.

Voice onset time (VOT), the time between the burst of energy in a consonant and the onset of voicing, is a crucial factor in determining which consonant is perceived (Pisoni, 1977). Recent experiments have shown correlations between VOT and gap detection and gap discrimination (Tyler, Summerfield, Wood, & Fernandes, 1982). Since implant patients' gap detection is normal, their perception of VOT may also be normal. VOT measures have not yet been made in implant patients.

While temporal processing in implants is somewhat normal, the frequency selectivity of electrical stimulation is completely different than in the normal cochlea. There is no frequency analysis of the electrical signal. This implies that the phase spectrum of a complex signal is important for the implant patient. Consider the time waveform of a complex stimulus, such as a series of harmonics. If all the harmonics are added in cosine phase, the resulting temporal waveform will be very peaked, approximating a pulse

train at the fundamental frequency. On the other hand, if the harmonics are added in random phase the resulting temporal waveform can have a low peak factor. To normal ears these two stimuli sound nearly identical; i.e., normal hearing is relatively insensitive to phase differences. However, to implant patients these two stimuli sound completely different in pitch, loudness and quality. In implants, the perception evoked is a complex function of the peak factor of the temporal waveform.

Now consider a speech waveform. In a normal room the time waveform of speech can be changed considerably as the talker changes position in the room. The echoes from the wall at each frequency add or subtract from the original energy at that frequency. For normal listeners this results in no change in quality or intelligibility as the talker's position changes. However, since the time waveform changes, the implant patients' perception of the same utterances can change dramatically as the talker changes position. Some of the differences observed between different implant devices may be caused by differences in the way the devices alter the phase spectrum. Changes in the phase spectrum of the stimulus may also result in apparent instabilities in the perceptions of implant patients. This problem can possibly be overcome by processing the speech waveform prior to delivery to the implant. New processing methods are being developed which extract features of the speech signal and stimulate the implant with the appropriate stimulus to produce the normal perception of that feature.

One point of emphasis: the perceptual effect of electrical frequency is *not* the same as the perceptual effect of acoustic frequency. Many people are led astray in applying principles of normal hearing to cochlear implant patients. Manipulating the electrical waveform in ways familar to normal acoustics (i.e., filtering, clipping) can have very different effects in implant patients than are observed in normal hearing patients. Electrical stimulation of the auditory nerve produces a different pattern of nerve activity than normal acoustic stimulation, and it produces a different pattern of perceptions. Successful application of implants depends on understanding the perceptual differences between electrical and acoustic stimulation. The acoustic environment must then be *translated* into an electrical signal in a way that preserves the relevant perceptual parameters of speech and everyday sounds.

ACKNOWLEDGMENT

This work supported by NIH Grant NS-11804.

REFERENCES

Atlas, L.E., Herndon, M.K., Simmons, F.B., Dent, L.J., & White, R.L. Results of stimulus and speech-coding schemes applied to multichannel electrodes. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York

Academy of Sciences, Volume 405, New York, 1983, 377-386.

Brummer, S.B., Robblee, L.S., & Hambrecht, F.T. Criteria for selecting electrodes for electrical stimulation: Theoretical and practical considerations. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 159-171.

Burns, E.M., & Viemeister, N.F. Nonspectral pitch. *Journal of the Acoustic Society of America,* 1976, *60,* 863-869.

Chouard, C.-H., Fugain, C., Meyer, B., & Lacome, H. Long-term results of the multichannel cochlear implant. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 387-411.

Clark, G.M., Shepherd, R.K., Patrick, J.F., Black, R.C., & Tong, Y.C. Design and fabrication of the banded electrode array. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 191-201.

Dillier, N., Spillman, T., & Guntentensperger, J. Computerized testing of signal-encoding strategies with round-window implants. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 361-369.

Djourno, A., & Eyries, C. Prosthese auditive par excitation electrique a distance du nerf sensoriel a l'aide d'un bobinage indus a demeure. *Presse Medicale,* 1957, *65,* 14-17.

Eddington, D.K., Dobelle, W.H., Brackman, D.E., Mladejovsky, M.G., & Parkin, J.L. Auditory prostheses research with multiple channel intracochlear stimulation in man. *Annals of Otology, Rhinology, and Laryngology,* 1978, *87,* Supplement 53, 1-39.

Eddington, D.K. Speech recognition in deaf subjects with multichannel intracochlear electrodes. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 241-258.

Edgerton, B.J., Doyle, K.J., Brimacombe, J.A., Danley, M.J., & Fretz, R.J. The effects of signal processing by the House-Urban single-channel stimulator on auditory perception abilities of patients with cochlear implants. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 311-322.

Fourcin, A.J., Douek, E.E., Moore, B.C.J., Rosen, S., Walliker, J.R., Howard, D.M., Abberton, E., & Frampton, S. Speech perception with promontory stimulation. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 280-294.

Guttman, R., & Hachmeister, L. Effect of calcium, temperature polarizing currents upon alternating current excitation of space-clamped squid axons. *Journal of General Physiology,* 1971, *58,* 104-154.

Hochmair, E.S., & Hochmair-Desoyer, I.J. An implanted auditory eight channel stimulator for the deaf. *Medical & Biological Engineering & Computing,* 1981, *19,* 141-148.

Hochmair, E.S., & Hochmair-Desoyer, I.J. Percepts elicited by different speech-coding strategies. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 268-279.

Hochmair-Desoyer, I.J., Hochmair, E.S., Burian, K., & Stiglbrunner, H.K. Percepts from the Vienna cochlear prosthesis. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 295-306.

Hochmair-Desoyer, I.J., Hochmair, E.S., & Burian, K. Design and fabrication of multiwire scala tympani electrodes. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An*

International Symposium. Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 173-182.

House, W.F. Cochlear implants. *Annals of Otology, Rhinology, and Laryngology,* 1976, *85,* Supplement 27, 1-93.

Leake-Jones, P.A., & Rebscher, S.J. Cochlear pathology with chronically implanted scala tympani electrodes. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 203-223.

Loeb, G.E., Byers, C.L., Rebscher, S.J., Casey, D.E., Fong, M.M., Schindler, R.A., Gray, R.F., & Merzenich, M.M. Design and fabrication of an experimental cochlear prosthesis. *Medical & Biological Engineering & Computing,* 1983, *21,* 241-254.

Muller, C.G. Survey of cochlear implant work. *Journal of the Acoustical Society of America,* 1981, *70,* S52.

Muller, C.G. Comparison of percepts found with cochlear implant devices. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 412-420.

O'Reilly, B.F. Probability of trauma and reliability of placement of a 20 mm long model human scala tympani electrode array. *Annals of Otology, Rhinology, and Laryngology,* 1981, *90,* Supplement 82, 11-12.

Owens, E., Kessler, D.K., & Raggio, M. Results for some patients with cochlear implants on the minimal auditory capabilities (MAC) battery. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear Prostheses: An International Symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 443-450.

Pfingst, B.E., Donaldson, J.A., Miller, J.M., & Spelman, F.A. Psychophysical evaluation of cochlear prostheses in a monkey model. *Annals of Otology, Rhinology, and Laryngology,* 1979, *88,* 613-625.

Pfingst, B.E., & Sutton, D. Relation of cochlear implant function to histopathology in monkeys. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear prostheses: An international symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 224-239.

Pfingst, B.E., Sutton, D., Miller, J.M., & Bohne, B.A. Cochlear implants: Relation of psychophysical measures to histological findings. *Acta Otolaryngolica,* 1981, *92,* 1-13.

Pisoni, D.B. Identification and discrimination of the relative onset time of two component tones: Implications for voicing perception in stops. *Journal of the Acoustical Society of America,* 1977, *61,* 1352-1361.

Plomp, R., & Bowman, M.A. Relation between hearing threshold and duration for tone pulses. *Journal of the Acoustical Society of America,* 1959, *31,* 749-758.

Shannon, R.V. Multichannel electrical stimulation of the auditory nerve in man. I. Basic psychophysics. *Hearing Research,* 1983a, *11,* 157-189.

Shannon, R.V. Multichannel electrical stimulation of the auditory nerve in man. II. Channel Interaction. *Hearing Research,* 1983b.

Simmons, F.B., Mathews, R.G., Walker, M.G., & White, R. A functioning multichannel auditory nerve stimulator. A preliminary report on two human volunteers. *Acta Otolaryngolica,* 179, *87,* 170-175.

Simmons, F.B. Percepts from modiolar (eighth nerve) stimulation. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear prostheses: An international symposium.* Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 259-263.

Stevens, S.S. The auditory input-output function. *Proceedings of the Third International Congress of Acoustics,* Elsevier, Amsterdam, 1960, 78-80.

Tong, Y.C., Clark, G.M., Blamey, P.J., Busby, P.A., & Dowell, R.C. Psychophysical studies for two multiple-channel cochlear implant patients. *Journal of the Acoustical Society of America,* 1982, *71,* 153-160.

Tong, Y.C., & Clark, G.M. Percepts from scala tympani stimulation. In C.W. Parkins & S.W. Anderson (Eds.), *Cochlear prostheses: An international symposium*. Annals of the New York Academy of Sciences, Volume 405, New York, 1983, 264-267.

Tyler, R.S., Summerfield, Q., Wood, E.J., & Fernandes, M.A. Psychoacoustical and phonetic temporal processing in normal and hearing-impaired listeners. *Journal of the Acoustical Society of America*, 1982, *72*, 740-752.

Walsh, S.M., & Leake-Jones, P.A. Chronic electrical stimulation of auditory nerve in cat: Physiological and histological results. *Hearing Research*, 1982, *7*, 281-304.

Zwislocki, J.J. Temporal summation of loudness: An analysis. *Journal of the Acoustical Society of America*, 1969, *46*, 431-441.