The Development of Speech Processing Strategies for the University of Melbourne/Cochlear Multiple Channel Implantable Hearing Prosthesis

Élaboration de stratégies sur le traitement de la parole pour l'implant cochléaire multi-canal de l'Université de Melbourne

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Abstract

The speech processing strategies that have been used with the University of Melbourne/Cochlear multiple channel implantable hearing prosthesis have been developed systematically from the inaugural one that extracted the second formant and presented this on a place coding basis and the voicing frequency which determined the rate of stimulation. Speech processing has also depended heavily on biological research to ensure that the stimulus parameters used or the operative approach did not damage the spiral ganglion cells it was hoped to stimulate. The advances in speech processing from Melbourne primarily have been to extract more features and spectral information and present this on a place coding basis. This has led to a progressive improvement in speech perception, and a small number of patients can achieve nearly 100% correct scores for open sets of phonetically-balanced words using electrical stimulation alone.

Résumé

Les stratégies sur le traitement de la parole qui ont été utilisées pour l'implant cochléaire multi-canal de l'Université de Melbourne ont été élaborées systématiquement à partir des premières stratégies, qui consistaient à extraire le deuxième formant et à le présenter en fonction du lieu d'articulation et de la fréquence de la voix, qui déterminait le taux de stimulation. En outre, le traitement de la parole a grandement été tributaire des recherches biologiques de façon à s'assurer que les paramètres des stimuli utilisés ou l'approche opératoire n'endommagent pas les cellules du ganglion spiral, qui devaient être stimulées. Les progrès réalisés dans le domaine du traitement de la parole, à Melbourne, visent principalement à obtenir d'autres caractéristiques et des renseignements spectraux et à présenter ces renseignements en fonction du lieu d'articulation. Cela a amené une amélioration considérable dans la perception de la parole, et un petit nombre de patients peuvent obtenir une note presque parfaite pour les ensembles ouverts de mots phonétiquement équilibrés en utilisant uniquement la stimulation électrique.

Introduction

Speech processing requires the extraction and analysis of the speech signal and its presentation to the auditory nervous system as coded electrical stimuli so that speech can be perceived. The coded signals are transmitted through the intact skin by inductive coupling to an implanted receiver/stimulator in the case of the Cochlear device. Residual auditory nerve fibers or ganglion cells are excited by electrical stimuli from an array of electrodes placed in the scala tympani of the basal turn of the cochlea.

The development of speech processing strategies depends in part on determining the speech signals that can be best used to stimulate the auditory nervous system to convey speech. In theory, the coded signals should simulate in the auditory nerve fibers the temporal and spatial patterns of action potentials seen when sounds excite the normal cochlea. This would be difficult, however, with any degree of precision as there are approximately 10,000 auditory nerve fibers in the human cochlea in the speech frequency range. The 22 electrode pairs on the Cochlear electrode array or the 10 stimulus channels used with the prototype University of Melbourne electrode and receiver/stimulator would not be enough. Therefore, it is necessary to know if speech processors can present speech as coded signals with a more limited number of stimulus channels and still adequately simulate the physiology. Alternatively, the speech processors should extract only the essential speech information that can be processed by the auditory nervous system via a relatively small number of stimulus channels. It is realized that the use of the word *channel* may imply that the information along each channel does not overlap the other, which is not usually the case. However, the use of multiple electrode stimulation can be even more confusing as it has been used in situations when single channel or global stimulation is really carried out.

Personal research commenced in 1967 in the Department of Physiology, University of Sydney, to help answer the question of how well speech processing could simulate the physiology. This research was carried out in the experimental animal prior to any research on patients. The study investigated the unit responses and field potentials from a second order auditory center in response to sound and electrical stimuli. A second order auditory nucleus was chosen to enable the effects of electrical stimulation to be examined at a higher center wherein more complex processing of stimuli occurs (e.g., complex inhibitory patterns). The study also investigated the neural responses to different frequencies or rates of acoustic and electrical stimuli. This research showed that the second order neurones would not follow electrical stimulus rates greater than 200 pulses/s without a decrement in response compared to acoustic stimuli.

The fact that for bursts of stimuli the patterns of cell firings were different for sound and electrical stimuli was attributed to the synchronous discharge of a number of nerve fibers that occurs with electrical stimuli. To help improve the situation and better simulate the coding of sound with a more asynchronous response, the effects of electrical sinusoidal and square waves were compared. However, no differences were observed.

Although electrical stimulation of the auditory nerve at rates greater than approximately 200 pulses/s could not reproduce the firing patterns seen when a cell responded to a sound, there was evidence in the study that cells which only responded to the rise and decay of a tone pulse could respond to an electrical stimulus in the same way over a wide range of stimulus rates.

The above study, carried out to help determine the extent to which electrical stimulation could simulate neural responses to sound, showed that there were limitations in using the volley theory or rate of stimulation to convey the middle to high frequency information of importance for speech intelligibility, and that place of stimulation probably would be required. In other words, a multiple channel rather than a single channel speech processor would be needed to provide adequate speech information. Furthermore, the fact that there was little difference between sinusoidal and square wave stimuli also suggested that sinusoidal stimulation would not be required for the prototype receiver/stimulator.

In 1969, following the above research study, it became clearer that to develop a cochlear implant to help people understand speech, further research in a number of areas would be needed. It would be necessary to extend the above study as well as determine the behavioral responses in the experimental animal to different rates of stimulation and other stimulus parameters. It would be necessary to determine how best to place electrodes within the cochlea and to isolate the current to discrete groups of nerve fibers to allow frequency coding on a place basis. It would be necessary to design an appropriate electrode array and ensure its biocompatability. It would also be necessary to learn what speech information to code and how to engineer a speech processor making it small enough to be used by patients in their every day life.

Future directions for a cochlear implant program were outlined in the Doctorate of Philosophy thesis by Clark (1969). These directions are quoted below.

> "...experience with direct electrical stimulation of the auditory nerve and its terminal fibres indicates that the surgical treatment of perceptive deafness is possible. A number of problems will have to be solved, however, before satisfactory speech intelligibility can be achieved.
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> Electrical stimulation of the auditory nerve could not be expected to produce hearing in patients with damage to the higher auditory centres. Many children and some adults with perceptive deafness, however, have a lesion involving the cochlea and not the higher centres (Ormorod, 1960) and could be helped when their deafness is severe. A number of patients with presbycusis also have a lesion involving the cochlea (Schuknecht, 1964), but their hearing loss is usually not severe enough to warrant this form of treatment.
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> It would also be desirable to have clinical tests which enable patients to be sorted into those most likely to benefit from the operation. Tests of speech intelligibility and the presence of recruitment are satisfactory when some residual hearing remains, but in the patients where severe or total deafness is present these methods would not be adequate. It is possible that an objective test of hearing using preliminary electrical stimulation of the cochlea could be devised.
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> The type of electrodes used and their method of implantation will also have to receive careful consideration. Simmons (1967) has shown that when electrodes are chronically implanted in the scala tympani of cats through an incision in the round window, the surgical trauma need not cause permanent cochlear damage. The factors responsible for degeneration of the organ of Corti and auditory nerve fibres were unpredictable; however, infection was found consistently to produce widespread destruction of tissue. Consequently, the site and method of implantation are important as the neural pathways can be damaged; this would prevent the electrical signals being transmitted to the higher centres. Destruction of the cochlea can lead to transneuronal degeneration in the cochlear and superior olivary nuclei up to a year after the production of the lesions (Powell & Erulkar, 1962).
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> Not only do these technical problems require solution, but also a greater understanding of the encoding of sound is desirable. As emphasized by Lawrence (1964), the terminal auditory nerve fibres are connected to the hair cells in a

complex manner, which could make it difficult for electrical stimulation to simulate sound. The relative importance of the volley and place theories in frequency coding is also relevant to the problem. If the volley theory is of great importance in coding frequency, would it be possible for different nerve fibres, conducting the same frequency information, to be stimulated in such a way that they fired in phase at stimulus rates greater than 100 pulses/s. If this were possible, it would then have to be decided whether this could be done by stimulating the auditory nerve as a whole, or whether local stimulation of different groups of nerve fibres in the cochlea would be sufficient. On the other hand, if the place theory is of great importance on coding frequency, would it matter whether the electrical stimulus caused excitation of nerve fibres at the same rate as an auditory stimulus, or could the nerve fibres passing to a particular portion of the basilar membrane be stimulated without their need to fire in phase with the stimulus?

If the answers to these questions indicate that stimulation of the auditory nerve fibres near their terminations in the cochlea is important, then it will be necessary to know more about the internal resistances and lines of current flow in the cochlea, and whether the electrical responses normally recorded are a reflection of the transduction of sound into nerve discharges, or directly responsible for stimulating the nerve endings.

The final criterion of success will be whether the patient can hear, and understand speech. If pure tone reproduction is not perfect, meaningful speech may still be perceived if speech can be analysed into its important components, and these used for electrical stimulation. More work is required, however, to decide which signals are of greatest importance in speech perception (Clark, 1969).

To help answer these questions research then commenced in the recently created Department of Otolaryngology, University of Melbourne, in January 1970.

Behavioral Studies on Frequency Coding

Prior to implanting our first patient a key issue for us continued to be the limitations of coding frequency on a rate basis (time period code) as this would determine whether we needed a single or multiple channel speech processor. It was felt that recordings made from the central auditory nuclei were not enough to resolve this issue as we could not be sure that the unit responses adequately reflected pitch perception. Therefore, a series of behavioral studies were undertaken in the cat, and these showed that the upper limits of their ability to discriminate changes in rate of stimulation were approximately: 200 pulses/s (Clark et al., 1972); 200-600 pulses/s (Clark et al., 1973); and 500 pulses/s (Williams et al., 1976). The experimental findings in these animals were similar to those subsequently obtained in patients, and they emphasize the importance of undertaking research in experimental animals prior to studies on humans.

Further behavioral studies were undertaken on experimental animals that were also subsequently of importance for the future development of speech processing strategies in implanted patients. These studies were aimed at determining whether the animals could perceive dynamic stimuli of importance for recognizing consonants. This was undertaken because consonants are very important for speech intelligibility. The dynamic stimuli chosen were frequency modulated electrical pulses. The ability of cats to detect changes in frequency or rate of stimulation was compared for sounds and for electrical stimuli.

The study was carried out by varying the slope or rate of change in stimulus rate or frequency for electrical stimuli of 200 pulses/s and 2000 pulses/s, and for sounds at 200 Hz and 2000 Hz. The carrier frequencies were modulated by triangular waves to produce graded changes in frequency over a duration of 500ms. The results for sound at 200 Hz and electrical stimuli at 200 pulses/s were similar. The thresholds at a 50% response level were 97 Hz/s for sound and 85 pulses/s for electrical stimuli. The ability of cats to detect changes in rate of stimulation at high stimulus rates of 2000 pulses/s was poor compared to that for sound at the same frequency.

It is of interest to compare the result in the cat, for change in rate of stimulation at 200 pulses/s, with that obtained subsequently on cochlear implant patients (Tong et al., 1982). In this latter study on patients, the electrical stimuli were varied from initial rates of 240, 210, 180, and 150 pulses/s to a final rate of 150 pulses/s over durations of 25, 50, and 200ms. The assessment procedure used for the patients was different from that for the cat study, but a low estimate of the rate of change in stimulus rate that could be detected was 300 pulses/s.

Because the ability of cats and humans in detecting changes in rate of stimulation at low frequencies was similar for electrical stimulation and sound, there was support for the use of rate in coding voicing, wherein a change in 200 Hz can be expected over the duration of a sentence of 2s (100 Hz/s). On the other hand, their inability to detect changes in stimulus rate at high frequencies indicates that rate is inappropriate for conveying the rapid frequency changes in consonants that can be as high as approximately 10,000 Hz/s (Clark & Tong, 1990).

Electrical Current Spread within the Cochlea

As there was increasing evidence that the rate of stimulation could not convey the mid to high frequencies required for consonant perception, it was considered important to determine how best to implant multiple electrodes in the cochlea to produce maximal channel separation or minimal cross talk between channels so that frequencies could be conveyed on a place basis. For this reason we carried out a series of computer modelling and animal experimental studies to determine the electrical resistances of structures within the cochlea and how the current would best flow between electrodes to excite groups of residual auditory nerve fibers. As a result of this study we concluded that the electrodes should be placed within the scala tympani and that bipolar or common ground stimulation would be satisfactory (Black & Clark, 1980).

Histopathological Effects of Cochlear Implantation

Not only was it necessary to know where best to place electrodes in the cochlea for optimal stimulation of discrete groups of auditory nerve fibers, but also it was essential to learn to what extent different placements would result in damage to the cochlea and loss of auditory nerve fibers (Clark et al., 1975). It was considered that there was not much advantage in developing a multiple channel, multiple electrode speech processor if the groups of residual nerves it was hoped to stimulate were lost in the process of implantation. Indeed, at the time there was considerable conservatism about any operation which introduced electrodes into the cochlea, and in some areas strong opposition. For this reason studies were undertaken on experimental animals, and these showed that trauma was least and ganglion cell loss minimal when a free fitting electrode array was inserted into the scala tympani of the basal turn of the cochlea through an opening in the round window membrane (Clark, 1977).

The Design of a Multiple Electrode Array: Biophysics and Bioengineering

Research was also undertaken to design electrodes for safe multiple channel stimulation. Initially in vitro studies were carried out to determine the degree of platinum dissolution with different stimulus parameters. This showed that dissolved platinum increased with current density and pulse duration (Black, 1978; Black & Hannaker, 1979). Maintaining a low current density became, therefore, a priority and this was achieved with the banded electrode array. The circumferential design of the banded electrode enabled large surface areas to be achieved at discrete points along the cochlea. The banded electrode array also had an advantage over other arrays that were moulded and had small electrodes in that the siting of the electrode was less critical (Clark et al., 1983). In other words it was more robust to variations in cochlear anatomy and pathology. Subsequently, in vivo studies were undertaken with this electrode array using stimulus parameters that were to be used in the (Nucleus) cochlear implant and speech processor for clinical trial (Shepherd et al., 1983). This research showed that, for charge densities less than 18-32mCcm^{-2}geom per phase, for stimulus levels halfway between threshold and discomfort level, and for a rate of 500 pulses/s, cats could be stimulated for periods of up to 2029 h without loss of spiral ganglion cells. These biophysical and biological studies applied constraints on the speech processing strategies to be used and were important for safety. It should also be emphasized that any significant change in speech processing should be accompanied by further safety studies.

The Design of an Implantable Receiver-Stimulator

In preparing to electrically stimulate patients and develop a speech processor not only was it necessary to do physiological, behavioral, and biological research on experimental animals to help determine safety and efficacy, but also it was desirable to produce a system for stimulating the residual auditory nerves in the cochlea that would result in the least discomfort and morbidity for the patient. In 1970 we realized that a percutaneous plug and socket in experimental animals frequently was accompanied by localized infection around the edges of the socket, and quite often it was damaged. It was considered the same would apply to the initial research patients. Although we would be limited in the range of stimulus parameters we could investigate using an implanted receiver-stimulator with a transcutaneous link because it would be less transparent than a direct percutaneous connection with wires, it was in the interests of our patients to develop a prototype implantable device and keep morbidity to a minimum. On the basis of our previous experimental animal physiological and psychophysical studies and a literature review, the University of Melbourne prototype receiver-stimulator was designed to be a constant current stimulator and produce biphasic pulses with a width of 0.18 ms. The stimulus current had a range from 70μA to 1000μA in 70μA steps, and it could provide ten channels of common ground stimulation. The pulse rate on each electrode could be varied in steps of 125 pulses/s up to 1000 pulses/s. It was also designed so that the timing of the pulses could be independently controlled on each electrode so that the fine time structure of pulses between channels could be studied (Clark et al., 1977). It was also necessary to evaluate the best way to transmit information and power to the device and how it should be packaged. At the time it was not clear if the data link should be ultrasound, infrared, or inductive coupling. After careful consideration, it was decided to use an RF inductive link because it was more robust. The same also applied to the decision to use digital rather than analog circuits. The electronics were constructed as a hybrid circuit because we were not sure what stimulus parameters would be most important to incorporate in the custom made silicon chip. The electronics were packaged in a gold plated Kovar container which had glass-to-metal seals for the exiting electrodes, and the two halves of the container were sealed with solder. The prototype container was eventually found to have design flaws, and this knowledge was helpful in making the Cochlear (Nucleus) receiver-stimulator for clinical trial more durable (Clark, 1987).

Initial Patient Investigations

When the initial University of Melbourne prototype receiver-stimulator had been checked, it was implanted (Clark et al., 1979) in our first patient (RS) on 1 August 1978. The patient was a 48 year old man who was postlinguistically deaf following a head injury received 18 months prior to his operation. He had a detailed audiological, clinical, and psychological investigation before surgery.

Because there was little information about how to process speech to help patients with speech perception at the time of this patient's operation, we decided to proceed on the bases described below. First, we initially would operate on only one patient so that we could minimize any risks and, by concentrating our investigations on him, have more opportunity to learn how to process speech. Second, we would divide our time between basic investigations to learn more about his perception and rehabilitation strategies to help in re-developing the ability to understand speech. To achieve a balance between acquiring knowledge and helping a patient is necessary with many research projects, and the two goals are not necessarily mutually exclusive.

Initially we had to carry out psychophysical investigations to see how to produce some speech perception before any rehabilitation could occur. Here again there was a dilemma: Should we undertake a whole series of psychophysical investigations to determine as precisely as possible the perception experienced for simple and complex stimuli or should we explore different ideas on how to process speech to give speech perception. After consideration it was decided to do both in parallel. We would do some essential psychophysics, evaluate a speech processing strategy, see what its limitations were, and then decide appropriate further psychophysical studies to help determine alternative speech processing strategies and so on.

Psychophysical Studies

Our preliminary psychophysical studies were carried out primarily to determine whether place pitch was conveyed by the electrodes at different locations within the cochlea (Tong et al., 1979). The difference limens for rate of stimulation and the thresholds and dynamic ranges for loudness at each electrode were also measured. During this series of experiments, it was noted that the patient described the sensations at each electrode as vowel like. When the vowels perceived were related to the site of stimulation, it was observed that there was quite good correspondence between the frequency of the second formant of that vowel and the frequency coded by the cochlea at that electrode location. Furthermore, it was noted that when the rate on an electrode was varied, a consonant was perceived. Whether this finding was due to a frequency or intensity change was not determined.

Speech Processing Strategy: Physiologically-based Studies

Having completed preliminary psychophysical studies and found that pitch was perceived on a place as well as rate basis, it was decided to evaluate a hard-wired speech processor that had been designed to simulate the spatial-temporal patterns of auditory nerve action potentials in response to sounds. The speech processor simulated neural firing patterns of single nerve fibers on 10 stimulus channels. Each channel presented the output from one of 10 overlapping band-pass filters. The filters were overlapped to simulate basilar membrane mechanics. The stimulus pulses were controlled by a stochastic circuit to simulate temporal neural firing patterns (Laird, 1979). Unfortunately, when this speech processor was evaluated on the patient, speech perception results were poor; this was found to be due in part to uncontrollable variations in loudness due to the simultaneous presentation of the stimuli (Clark, 1987). As a result, it was concluded that further progress would be made by presenting stimuli non-simultaneously and that some form of preprocessing would be needed.

Inaugural Speech Processing Strategy: Formant Extraction

A speech processing strategy was then conceived which extracted the second formant frequency (F2) and presented this to an appropriate electrode for that frequency at a current level proportional to the output of the F2 filter. It also extracted the voicing or fundamental frequency (FO) and stimulated the F2 electrodes at a rate proportional to that frequency (Tong et al., 1980 a,b). The stimuli were all presented non-simultaneously to avoid the problem of unpredictable interactions in the electrical field.

This speech processing strategy developed first on a main frame computer was found to provide the first patient with open set speech recognition when electrical stimulation was used alone, and he obtained considerable improvement in understanding speech when electrical stimulation was combined with lipreading compared to lipreading alone (Clark et al., 1981 a,b).

As a result of the encouraging results on one patient it was considered appropriate to validate the findings on a second postlinguistically deaf person (GW1) to see if the strategy would apply to others. The second patient who had his operation on 17 July 1979 had been profoundly, totally deaf for a considerably longer period of time (13 years) than the first patient. Therefore, in his case we were concerned to know not only would the strategy work on others, but also would his auditory memory for speech sounds still be present after 13 years and would the longer duration of deafness have affected the central auditory pathways so that they would not adequately respond to electrical stimulation. It was pleasing at his first and second test sessions to find that he could understand running speech especially when combined with lipreading. Although not a standard test, we bought a copy of the daily newspaper, read a difficult section to him, and found he could get most of the information correctly when it was re-read without lipreading assistance.

Industrial Development of Receiver-Stimulator and Inaugural Speech Processor

In view of the successful results on the first two patients, industry was approached with a view to developing the device commercially. The firm, Teletronics, expressed interest and was chosen because of its proven expertise in pacemaking and its ability to package electronics for implantation. This firm had pioneered the ceramic-to-metal seal that enabled electrodes to exit from implanted packages without creating a fluid entry path. The firm later became incorporated in a holding company, Nucleus Limited. Later again, Nucleus formed a subsidiary, Cochlear Pty Limited, which was responsible for the development and marketing of the cochlear implant.

The task for Teletronics was to produce for clinical trial a more robust and efficient implantable receiver-stimulator than the University of Melbourne's prototype, and a speech processor that would enable the University of Melbourne's speech processing strategy to be implemented as a smaller pocket-sized device. The receiver-stimulator had its electronics incorporated on to a single custom-made silicon chip. This was packaged in a titanium capsule with its two halves welded together. Twenty-two (22) electrodes emerged through a ceramic-to-metal seal, and there was one receiving coil of platinum wire around the capsule. This received both power and data. The receiver-stimulator also had a connector so that it could be disconnected and exchanged for another package should it fail or need upgrading. At this stage of the development, although we knew that banded electrode arrays could be easily removed from cats, we had no experience in the human of either explantation or reimplantation of the array. For this reason, we felt it was desirable to incorporate a connector. Later, however, with experience in removing electrode arrays together with the University of Melbourne's prototype receiver-stimulator and replacing them with the new Cochlear device, we came to realize that a connector would probably not be necessary.

The electronics for the receiver-stimulator were designed to provide a greater range of stimulus parameters in some areas and less in others than the University of Melbourne's prototype device. This was determined on the basis of experience with the prototype. Bipolar as well as common ground stimulation was made available to allow more stimulus channels to be used. The facility to vary the passage of current between either adjacent or more remote electrodes was incorporated. It was also possible to provide monopolar stimulation by using the common ground mode with an external electrode. More amplitude steps were created and they could be varied over the range from 25μA to 1.5μA in 3% steps. The device also had a facility wherein the pulse width could be varied as well as the amplitude from 20ms to 400ms per phase in steps of 0.4ms.

Clinical Trial of Nucleus Cochlear Implant

The Nucleus cochlear implant was trialled first on six postlinguistically deaf adults operated on at the Royal Victorian Eye & Ear Hospital from September to December 1982. This trial was an important part of the industrial development of the device as it was necessary to confirm that it could be engineered to meet specifications and be of benefit to a wide range of deaf people. The overall results for help with lipreading were at least as good as those obtained with the first two patients who had the University of Melbourne's prototype. Patients were also able to get open set speech recognition using electrical stimulation alone (Clark et al., 1983 a,b; Dowell et al., 1984). With the first four of these patients, three obtained open set AB word scores for electrical stimulation alone which varied from 10% to 37% (Clark et al., 1983 a,b; Dowell et al., 1984).

The next significant step in the development of speech processing strategies for the multiple channel implant was to extend the clinical trial to other centers and obtain approval from the US Food and Drug Administration (FDA) that the device was both safe and effective. The extension of the trial to other centers in the US, Canada, West Germany, and Australia was requested by the FDA to ensure that experimental bias was not a factor and that a larger population of deaf patients would benefit. The FDA also required additional studies to ensure the safety of the device. Some of these were undertaken by the Department of Otolaryngology, University of Melbourne (Clark, 1987). The results of the extended clinical trial were essentially similar to those obtained from the initial clinical trial in Melbourne, and the FDA approved the device as safe and effective for postlinguistically deaf adults in October 1985.

At about the same time, there was a debate that the results with single channel stimulation were as good as those with multiple channel stimulation. This debate was due to a number of factors. There were differences in defining multiple electrode and multiple channel stimulation, but above all there was disagreement in interpreting the meaning of open set tests. This was clarified by specifying that open set tests are those which come from an unlimited and preferably standardized list of words and are presented under controlled conditions. These conditions should be: no prior practice, pre-recorded material, unfamiliar speaker, and standardized sound conditions in the test room.

To help resolve the controversy we compared the results for a test of closed sets of spondaic words on our first two postlingually deaf patients with the results for nine patients at the House Ear Institute using their single channel device. The test was carried out as reported (Bilger, 1977) and results compared using the Wilcoxan Rank Sum test. The results were significantly better for the University of Melbourne's multiple channel device (Clark et al., 1981c). A comparison was also made in our first patient between a speech processor that provided fundamental or FO information via single channel stimulation and the FO/F2 multiple channel device. The comparison was made on the basis of consonant speech feature information transmission and speech perception scores. The results showed a significantly better performance for the FO/F2 processor for almost all tests except voicing information (Clark et al., 1984).

Our two comparative studies, discussed above, lacked either an adequate number of patients or compared results between clinics. These limitations were finally avoided in a study at Iowa in which comparisons were made under the same controlled conditions (Gantz et al., 1987). The devices compared were the 3M/House single channel, 3M/Vienna single channel, Symbion multiple channel, and Nucleus (FO/F2) multiple channel prostheses. The comparison showed that speech perception results were significantly better for multiple rather than single channel stimulation. The results for the two multiple channel prostheses were similar in quiet, but the Symbion device was better in noise. Although the feature extraction methods used for the Nucleus FO/F2 speech processor could have been more corrupted by noise than with the spectral analysis used by the Symbion device, the explanation is not as simple as this. It could also have been due to the microphones used, electronic noise, and/or related to the method of stimulating different channels.

The Second Generation Speech Processor: Formant Extraction—FO/F1/F2 (WSPIII)

While the clinical trials described above were being undertaken to assess the efficacy of the Nucleus FO/F2 speech processor, our research from 1982 was directed towards finding improved methods of speech processing which would result in better consonant recognition in particular, as well as improving speech perception in noise. The initial aim of the studies was to determine whether adding more formants (the first formant, F1, in particular) would improve the FO/F2 speech processor. To help answer this question a psychophysical study was undertaken to see if an additional stimulus presented on a place basis could be detected. The results (Tong et al., 1983) showed that two components were perceived when two pairs of electrodes were activated. This suggested that a speech processing strategy that converted acoustic first and second formants to electrical stimulation at two separate sites should be possible. To further assess this possibility, we developed an acoustic model for electrical stimulation using the FO/F2 speech processor (Blamey et al., 1984a). When the model had F1 added, it was found to result in an increase in the total information transmitted (Blamey et al., 1984b). The addition of F1 helped in the transmission of all speech features except place. In this study (Blamey et al., 1984b) we also determined that the amplitude envelope was an important cue for consonant recognition, and the addition of F1 resulted in better amplitude detection.

Having shown with the acoustic model that an FO/F1/F2 speech processor gave better results than the FO/F2 processor, this strategy was implemented by the University of Melbourne and Cochlear in a bench-top laboratory-based speech processor. When the FO/F1/F2 strategy initially was tested in a pilot study on a small number of patients who had been using the FO/F2 processor, a conclusive improvement was not seen. It was discovered that the patients had some difficulties learning the new strategy and would need a wearable take home unit before a satisfactory comparison could be made. As a result, Cochlear proceeded to implement the FO/F1/F2 strategy as a wearable unit called WSPIII. When it was trialled in patients, it was found to result in similar improvements to those obtained with the acoustic model (Clark, 1986; Dowell et al., 1987). This result showed the predictive value of the acoustic model and, in doing so, indicated it was a good model for formant-based speech processors using multiple channel electrical stimulation.

The FO/F1/F2 speech processor not only provided better speech perception results in quiet than the FO/F2 processor, but also performed better in noise (Dowell et al., 1987). Furthermore, the results in noise were as good as those obtained for the Symbion speech processor using the same test procedure described by Gantz et al. (1987). This FO/F1/F2 (WSPIII) speech processor was approved by the FDA in May 1986 for postlingually deaf adults.

Cochlear Implantation for Prelinguistically Deaf Adults and Children

While undertaking the further speech processing research on postlinguistically deaf patients, discussed above, we commenced studies in parallel to determine how to process speech for prelinguistically deaf people. The first prelinguistically deaf patient (GW2) to receive the multiple channel implant was educated almost entirely by signing (signed English and sign language) and was implanted on 20 September 1983 at age 25. A second patient (BK), who had a similar educational history, had an implant on 15 November 1983 at age 24 (Clark et al., 1987a,b). Both were studied extensively, and it was found from psychophysical research that although they performed well for current level identification and had satisfactory duration difference limens, their abilities for pulse rate and electrode position identification were poor (Tong et al., 1986; Clark et al., 1987a,b; Tong et al., 1988). This was also reflected in the poor speech perception scores they obtained using the formant-based speech processing strategy (Busby et al., 1986; Clark et al., 1987; Tong et al., 1988). From this study it was concluded that the formant-based speech processing strategy used for postlinguistically deaf patients was probably not suitable for prelinguistically deaf people twenty years of age and over, and that the use of signing could have been a contributing detrimental factor. It certainly reduced their motivation to learn a new and auditory/oral based system. It was also felt that untreated deafness from an early age could lead to perceptual processing difficulties for frequency coding that could make speech processing using those cues unsatisfactory.

In view of the above findings it was decided to operate on younger people, and preferably those with an auditory/oral educational background. On 8 January 1985 a 14 year old boy (PS) who had been taught with cued speech received a cochlear implant. His electrode place and pulse rate identifications were better than the two adult prelinguistically deaf patients, but not as good as those generally obtained for postlinguistically deaf people (Clark et al., 1987a). His speech perception was also better than the prelinguistically deaf adults, and he obtained some help in understanding running speech when the implant was used in combination with lipreading.

Some months later (17 September 1985) we implanted a 22 year old prelinguistically deaf woman who had received an auditory/oral education, and although born with a severe hearing loss, went profoundly-totally deaf over the first 18 years of her life. Interestingly, the speech perception results on this patient were more similar to those obtained with postlinguistically deaf people (Clark et al., 1987a).

As the results on the third patient (PS) had suggested that it was desirable to operate on younger children, the decision was made to implant a 10 year old. This child (SS) had a profound, total hearing loss at 3.5 years of age and was educated by total communication. The operation was only possible, however, with the development of the mini 22-electrode receiver-stimulator (Clark et al., 1987b), which was more suitable for children because it was smaller and had a rare earth magnet embedded in it (Dormer et al., 1980) so that an external transmitting coil, also with embedded magnet, could be held in place by bringing the magnets into close proximity. This new mini-22 prosthesis was implanted first in the 10 year old on 20 August 1985. After establishing that it performed to specifications, a series of psychophysical and speech perception studies were undertaken, and these demonstrated an advantage for the perception of speech when the device was combined with lipreading, but little open set speech recognition for electrical stimulation alone.

To evaluate the prosthesis on younger patients, a five year old (BD) received a cochlear implant on 15 April 1986. This boy, who went deaf at three years of age from meningitis and was trained with cued speech, made excellent progress with the implant and after some months was able to get significant open set speech identification scores from electrical stimulation alone.

Prior to implanting children, it was also realized that the training and assessment would need to be quite different from that for postlinguistically deaf adults. It was considered important that we assess not only speech perception, but also speech production as well as expressive and receptive language and communication skills (Nienhuys et al., 1987). To this end a protocol was developed which has been used subsequently for the management of all our children.

The studies on children at the University of Melbourne and the Australian Bionic Ear & Hearing Research Institute have continued since that time, and congenitally deaf children as young as two years of age have been operated on. It has been found that congenitally and prelinguistically deaf children benefit from the implant as well as postlinguistically deaf children, and a significant proportion can get open set speech recognition for electrical stimulation alone (Dawson et al., in press). The prelinguistically deaf group, however, need a longer period of training and appear to do better if implanted at a young age.

The evaluation of children using the WSPIII (FO/F1/F2) speech processor was extended to centres in North America and Australia for the FDA study. The results in 80 children were presented to the FDA, and it was approved as safe and effective for children on 27 June 1990. Since that time the results on 142 children have been analyzed (Staller et al., in press; Clark et al., in press) and they confirm the above findings from the University of Melbourne that pre- and postlinguistically deaf children can receive significant improvements when the device is combined with lipreading, and approximately 40-50% can get significant open set speech scores for electrical stimulation alone.

Figure 1. Open set sentence and closed set consonant and vowel scores for the prototype (FO/F2), WSPIII (FO/F1/F2), and MSP (Multipeak) speech processors using electrical stimulation alone.

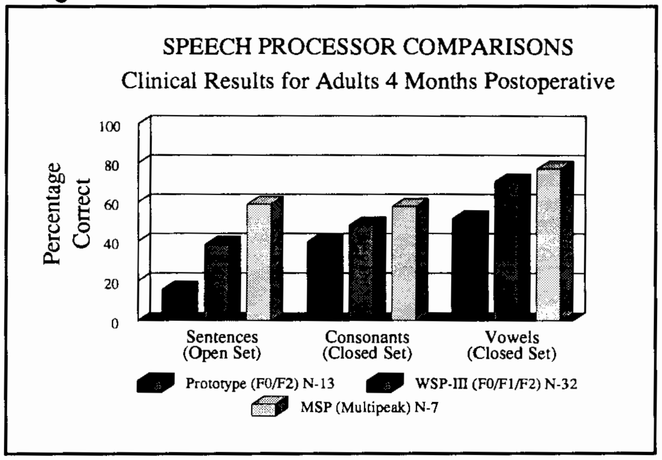
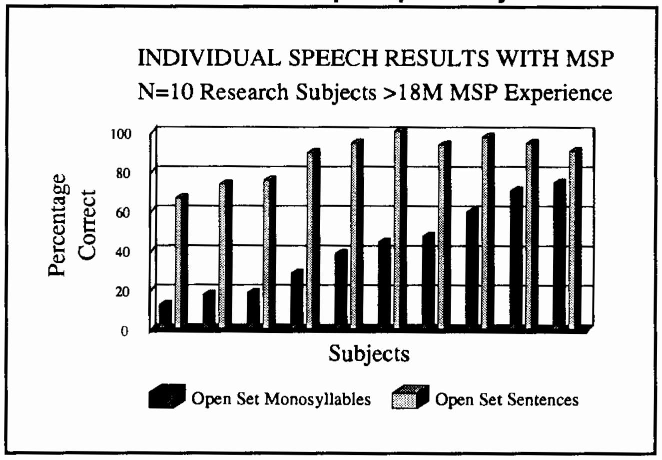


Figure 2. Open set monosyllable and sentence scores for 10 research subjects using the MSP speech processor. Results obtained 18 months postoperatively.



The Third Generation Speech Processor: Formant Extraction and High Frequency Spectral Peaks (Multipeak-MSP)

While establishing that the FO/F1/F2 speech processing strategy (WSPIII) would help profoundly deaf children as well as adults understand running speech, research was also in progress to further improve the speech processing strategy. The motivation for this was that, although there was significant improvement in the speech perception scores for the FO/F1/F2 compared to the FO/F2 processor, the results still fell short of the hoped for near normal findings for all patients. Furthermore, although there was a generally improved performance in noise, the consonant scores did not change markedly except for those in which the addition of F1 improved the transmission of voicing. To help overcome the information bottle-neck for electroneural stimulation that was particularly prominent for consonant perception, it was hypothesized that additional high frequency spectral information would help. The speech processor was accordingly modified so that in addition to the FO/F1/F2 processor, the amplitude of the three high frequency filters (ranges: 2000 Hz to 2800 Hz; 2800 Hz to 4000 Hz; and 4000 Hz to 6000 Hz) were determined. For voiced sounds, the outputs from the lower two frequency bands were used to stimulate the more apical two of three fixed electrodes in the high frequency end of the cochlea. For unvoiced sounds the amplitudes at the three high frequency filters were used to excite the three fixed electrodes and, in addition, the F2 but not F1 amplitude was used to stimulate a fourth electrode whose location was appropriate for the F2 frequency.

This strategy which presented informaion from four spectral peaks for each glottal pulse was named Multipeak and was implemented as a smaller wearable speech processor (MSP) by Cochlear Pty. Limited. The initial comparison of the MSP with the WSPIII speech processor at the University of Melbourne showed there was significant improvement in the perception of speech both in quiet and in noise (Dowell et al., 1990). A more detailed comparison of the two speech processors has also been made by Skinner et al. (1991) in a controlled study on five patients and by Dowell (1991) also in a controlled study on five patients. These studies show significant improvement for most elements of speech perception in quiet and noise. The scores for closed sets of both vowels and consonants were better, and this applied to place information for consonants.

Although not a controlled study, the progressive improvement that has been obtained with three generations of feature extraction and spectrally based speech processing schemes (FO/F2; FO/F1/F2 (WSPIII); FO/F1/F2 plus high frequency spectral peaks (MSP)) is approximated by the results shown in Figure 1 for groups of adults at the four month postoperative stage. With training and continued usage the results with MSP-Multipeak have continued to improve, and Figure 2 shows the open set monosyllable and sentence scores for electrical stimulation alone for 10 research subjects who have had 18 months experience with the speech processor. As can be seen, many open set sentence scores for electrical stimulation alone were at the 90% level or above, and the open set monosyllable scores were reaching 70%. The MSP-Multipeak speech processor was approved by the FDA in October 1989.

The Fourth Generation Speech Processor: Spectral Maxima

While research was being undertaken to develop a speech processor that extracted a number of formant and high fre-

Figure 3. Open set sentences (scored as words and phonemes) and closed set consonant and vowel scores for electrical stimulation alone are shown for three of four patients using the SMSP and MSP speech processors. The results for the SMSP are after only 1.5-3 months use.

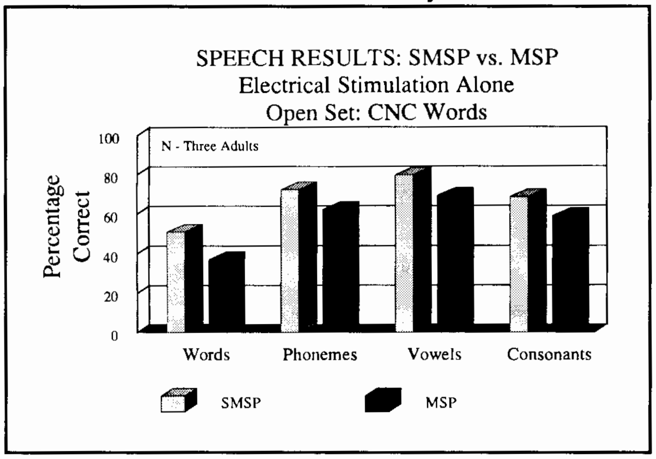
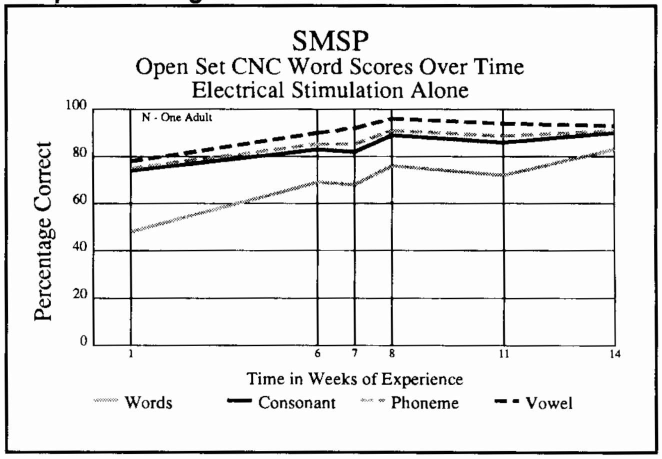


Figure 4. SMSP open set CNC word scores over time for one patient using electrical stimulation alone.



quency spatial peaks (MSP-Multipeak), a parallel line of research was also undertaken at the University of Melbourne and Australian Bionic Ear & Hearing Research Institute to determine whether six stimulus channels selected to best represent the maximal spectral energies of speech would be a better alternative. With this strategy (SMSP) the six spectral maxima from the outputs of 16 band-pass filters were used to stimulate the cochlea on a place basis at a constant rate rather than the voicing frequency, which is the case with the Multipeak-MSP device. More specifically, 16 overlapping frequency bands from a filter bank are mapped on to 16 electrode pairs (usually the most apical). The six highest amplitudes from the filters are presented to the appropriate electrode pairs using a similar mapping of amplitude to current/pulse width as is used in Cochlear's standard MSP processor. The rate of sampling of the filterbank output is 250 Hz, so six biphasic pulses are presented every 4 ms. Unlike the MSP strategy, there is no attempt to extract FO information (there is no specific coding of fundamental frequency information) or to find the formant peaks in the speech signal.

The new Spectral Maxima Speech Processor (SMSP) has been compared with the Multipeak-MSP in four patients (McKay et al., 1991a,b). The results of a detailed study show that both in quiet and noise the SMSP is performing better than the Multipeak-MSP. The mean results for open sets of sentences scored as words and phonemes and closed sets of consonants and vowels for electrical stimulation alone for both SMSP and Multipeak-MSP are shown in Figure 3. The improvements seen for the SMSP over the Multipeak-MSP were statistically significant.

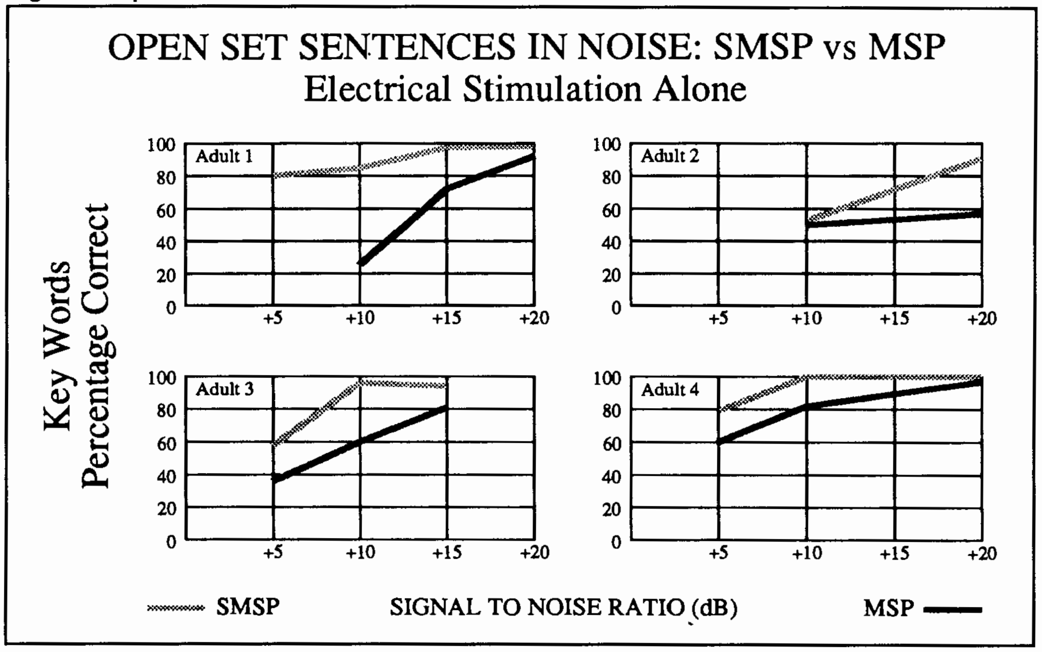
Furthermore, after experience with the device, three of the four patients are achieving open set scores for CNC words using electrical stimulation alone at the 80% correct levels. These are good scores, and when it is considered that when our first patient was implanted any score above 0% was above expectations and that today many severely deaf people with some residual hearing and wearing a conventional hearing aid do not score above 20%-50%, the results are even more exciting. An example of the improvements over time seen as patients gain more experience in the use of the speech processor is shown for one patient in Figure 4.

The other important finding from the study so far has been that SMSP has performed better in noise than the Multipeak-MSP device. The results for the four patients tested are shown in Figure 5. As can be seen, as the signal-to-noise ratio gets smaller, the gap in performance increases, indicating the performance of the SMSP is better. This is an encouraging finding particularly because Multipeak-MSP performed better in noise than previous strategies.

Conclusion

The speech processor research has involved a sequence of tasks that were interdependent. Some were carried out in series and others in parallel. In much of the speech processor research there has been a heavy dependence on technological advances. Speech processor research cannot easily be divorced from the communication engineering required to analyze the speech signal or minimize the use of power so the device can be made portable. Similarly, in using signals to stimulate the auditory neural pathways, there is a dependence on materials and electronic engineering to produce a receiver-stimulator device that is both safe and effective.

Figure 5. Open set sentence scores in noise: SMSP vs. MSP for four adults.



The development of appropriate methods for interfacing speech processors to the auditory nervous system has been dependent on biology, electrophysiology, anatomy and pathology, and otology. The appropriate assessment of speech processor performance in patients has required audiological and speech pathological tests. The advent of cochlear implants has also been a stimulus to these fields because it has meant a greater interest in developing tests and rehabilitation strategies for people with a profound-total hearing loss.

One is mindful in presenting this case study on the development of speech processing strategies for the University of Melbourne/Cochlear multiple channel implantable hearing prosthesis that other centers have contributed much to the development of cochlear prostheses in general. In our own case, all the relevant research of necessity had to be carried out at the one location, and this has permitted an analysis to be made first hand of the way in which factors operated for the development of a multiple channel speech processing system. Furthermore, we have reviewed the general field of speech processing for cochlear implants in the following publications: Miller et al., 1984; Miller et al., 1990; Miller et al., 1991.

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