CLOSING ADDRESS

COCHLEAR IMPLANTS: FUTURE RESEARCH DIRECTIONS

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The future of cochlear implants for profoundly deaf people now seems assured, and further research should improve its benefits. The present benefits of cochlear implants have now been clearly demonstrated. The results have shown that many postlingually deaf adults get significant open-set speech recognition using electrical stimulation alone, and that profoundly deaf children with a cochlear implant get better speech perception than similar children who use hearing aids or tactile vocoders.

To date, most of our speech-processing advances have occurred through the presentation of more speech cues and spectral information on a place-coding basis. The improvements with our own strategies can be seen in Fig 1. This Figure shows that speech perception scores have continued to rise and not plateau, suggesting that further improvements are possible.

The mean results for profoundly deaf people using an implant and current speech-processing strategies\(^1\) are now better than results for some severely to profoundly deaf people using a hearing aid. It is also pleasing that many prelingually and postlingually deaf children do better with an implant than either a hearing aid or a tactile vocoder (Geers et al, this suppl, section 15). This means that the implant will in the future be suitable for more deaf people.

In spite of the good overall results obtained with current speech-processing strategies, there is still a large distribution in performance levels, and some users do quite poorly. The challenge now is to develop new strategies that will not only further improve overall speech perception performance, but ensure that poor performers gain the same improvements as the better performers.

A large number of new strategies can now be evaluated.

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**Open Set Monosyllables**

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<tr>
<th>% Words Correct Hearing Alone</th>
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Fig 1. Average open-set monosyllable scores in groups of research patients for electrical stimulation alone with inaugural F0/F2, F0/F2 (WSP), F0/F1/F2 (WSPIII), hybrid F0/F1/F2 + high-frequency fixed filters (MPEAK), and roving filter or spectral maxima speech-processing (Spectra 22/SPEAK) strategies.

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**Cochlear model response for a 1 kHz stimulus**


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**Neely and Kim**\(^2\) frequency domain model, modified to make it stable in temporal domain.
with research speech processors that have digital signal processing or DSP chips. The DSP research processor, developed in our Human Communication Research Centre in 1991, was used to evaluate the spectral maxima strategy. This speech processor can be used with the new Cochlear Pty Limited micro-receiver-stimulator. The microimplant will allow the use of higher rates of stimulation than previously, as well as telemetry. Future improvements in cochlear implant speech processing are most likely to occur with better temporal and place coding of frequency information. The temporal coding of frequency occurs when an ensemble of fibers fire in phase with the sound wave. This is illustrated in Fig 2, where it can be seen that although each fiber does not fire each sine wave, the population as a whole does. There must therefore be a central mechanism for decoding frequency by responding to the population of interspike intervals (Clark et al, this suppl, section 5).

To achieve better temporal coding, we have developed a model of electrical stimulation to simulate the fine temporal pattern of action potentials in an ensemble of nerve fibers. This has been done by varying the number of pulses per period, as well as their relative amplitudes (Irlicht et al, this suppl, section 16). With the model, the patterns of stimuli are designed to take advantage of the refractory periods of nerve fibers so that some, but not others, will be stimulated with each pulse. The temporal patterns of action potentials in the auditory nerve also depend on the time course of the basilar membrane traveling wave. The traveling wave motion has been modeled (Au et al, this suppl, section 16) by modifying...
the Neely and Kim\textsuperscript{2} frequency domain model to make it stable in the temporal domain. This makes it capable of representing a time-varying input such as speech and predicting the phase as well as the amplitude of vibration. The basilar membrane model is illustrated in Fig 3.\textsuperscript{2} This basilar membrane model has been combined with the neural model to better represent the temporal patterns of nerve action potentials in an ensemble of auditory nerve fibers (Fig 4).

Place coding of frequency, in contrast to temporal coding, depends primarily on the filter characteristics of the basilar membrane, and leads to excitation of discrete groups of nerve fibers. However, when auditory nerve fibers are stimulated by electrodes in the scala tympani, the area of excitation is not as sharply tuned as for sound.\textsuperscript{3} Future research needs to be directed toward improving current localization. Our present research has found this can be done by placing electrodes closer to the modiolus,\textsuperscript{4} using electrodes that curl when they are inserted and absorb water\textsuperscript{5} (Fig 5). By placing electrodes closer to the spiral ganglion cells, electrical stimulation will also result in lower thresholds and charge densities. This would mean smaller electrodes could be used and therefore more could be placed in the cochlea for place coding.

Not all patients are going to benefit by improving temporal and place coding of frequency, as they may not have sufficient nerve fibers to process the information. These patients, who are likely to be poor performers, may be helped in the future by the use of automatic speech recognition to recognize the words, and the presentation of the words, as appropriate stimulus tokens. We now have the electronic processing capacity to do the analyses in real time, but research is needed to provide better speaker recognition and determine how best to represent the tokens. Neural networks are one means of automatically recognizing phonemes spoken by different speakers. We are undertaking research to improve the performance of neural networks. This is being undertaken by studying neural connections in the cochlear nucleus by means of biophysical models.

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**Fig 7.** Bipolar stimulation. Triangles point to responding neurons. A) Normal-hearing animal. B) Neonatally deafened, unstimulated animal. C) Neonatally deafened, chronically stimulated animal.
of electrical stimulation and neurohistologic techniques, and developing an improved neural network based on the connections in this nucleus.

The future coding strategies discussed above are for postlingually deaf people, as they depend on the connections in the central auditory nervous system that have resulted from prior exposure to sound. Future research must also examine how electrical stimulation at an early age affects neural connections, and how this in turn will influence speech-coding strategies for infants and young children. The effect of electrical stimulation on the development of neural connections is illustrated in Figs 6 and 7. Figure 6 shows that in young animals deafened 10 days after birth, chronic monopolar electrical stimulation for 1,000 hours produced a broadening in the band of excited neurons, compared to the group that were deafened but received no chronic stimulation. On the other hand, in another study (Fig 7), chronic bipolar stimulation produced the same band of excitation as for deafened animals with no chronic stimulation and for normal-hearing animals with acoustic stimulation. These results indicate that current spread, which can vary with stimulus mode, can affect the spatial development of neural connections, and this could influence place pitch perception.

As the ability to hear in the presence of background noise is very important, future research will also need to be undertaken to design systems that use single and dual microphones and "intelligent" speech processing to obtain a clearer speech signal in the presence of noise. One method we have been assessing is adaptive beamforming. The Griffiths-Jim beamforming system, used with hearing aids, has been applied to the cochlear implant (also van Hoesel et al, this suppl, section 12). The beamforming system is illustrated in Fig 8. This shows that for the beamformer the signal in the right ear will be S + N1 and the left ear S + N2. The signal goes into a summer that has an output S + N1 + N2 and a subtractor N2 - N1. The next stage (AFIR) adjusts the N2 - N1 to approximate N2 + N1 so that when one output is subtracted from the other the signal S2 is relatively free of noise. The results using this beamforming system in implant patients are shown in Fig 9, and indicate that there are very significant improve-
ments in the presence of background noise. Significant improvements in speech perception in noise should also be possible with bilateral cochlear implants, in the same way that we have an advantage with two hearing ears. We have already demonstrated this in two bilateral implant patients. Their results are shown in Fig 10.

Further research on the interaction between the inputs from cochlear implants on each side should also lead to the development of strategies that are better in quiet than those currently available. Two possible strategies are illustrated in Fig 11. In one it is proposed that monaural information be distributed between two cochlear implants, and in the other, that intelligent processing of information from two microphones be presented appropriately to two cochlear implants.

As the results with monaural cochlear implants for postlingually deaf adults are better than many severely to profoundly deaf people obtain with conventional hearing aids, there is a need to consider operating on patients who have some residual hearing. A small proportion of these patients will have an asymmetric hearing loss with a poorer ear that can receive surgery. In these patients there may be advantages in combining the inputs from the implant in one ear and any residual hearing with an aid in the other. About a third of patients with this arrangement get benefits from using both devices together. Some find the two are in conflict. Presently, we are examining the interactions between the aided and implanted ears and are finding that by the careful selection of electrode place or appropriate current-to-loudness transforms, a speech-processing strategy can be developed that is better blended and gives improved results. The concept underlying this bimodal speech-processing strategy used in the Combionic Aid is illustrated in Fig 12.

Many patients with some residual hearing who need an implant will have, however, symmetric hearing losses. When three-frequency average hearing thresholds were analyzed by Dr H. Dillon on 219 pensioners tested at the Australian National Acoustic Laboratories, 64% had a difference of less than 10 dB. This suggests that there will be a need to operate on people with some usable hearing in the implanted ear. Future research will need to be directed toward finding out to what extent residual hair cells can be preserved in the implanted ear, and how best to excite these hair cells either acoustically or electrophonically. We have commenced basic biological and physiological studies in this area. In a number of biological studies on cats and monkeys we have demonstrated that hair cells are prevalent in the middle and apical turns. Behavioral studies in chronically implanted cats and acute electrically evoked auditory brain stem response and masking studies have also shown these hair cells are functional and can be stimulated electrophonically. The research has also shown that electrophonic hearing is due to electromechanical stimulation of the basilar membrane at the site of the electrode and the propagation of a traveling wave to the site of maximal vibration for that particular frequency.

Fig 13. Design concept for totally implantable speech processor and receiver-stimulator.

Fig 14. Tympanic membrane vibration sensor consisting of small magnet coupled electromagnetically to multiple-coil unit.
would then carry out the speech processing and electrically excite the auditory nerves in the cochlea. The sensor would not result in an increased impedance. The sensor could consist of a small magnet weighing less than the malleus attached to the tympanic membrane. This could be coupled electromagnetically to a multiple-coil unit placed in close proximity, as illustrated in Fig 14.

Finally, future research will also need to be directed toward auditory nerve and cochlear hair cell regrowth. This has been shown to be possible in the experimental animal, and Fig 15 is a photomicrograph of hair cell regrowth in the chick.

In conclusion, although the future of cochlear implants seems assured, one day, regeneration of hair cells and nerve fibers may challenge this position.

REFERENCES


