Cochlear Implants in the Third Millennium

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SELECTED ACHIEVEMENTS IN THE SECOND MILLENNIUM

Before outlining some important directions for cochlear implant research in the Third Millennium, it is worth reviewing a few of the achievements of the Second Millennium.

As recently as the 1960s and 1970s, many scientists and clinicians claimed that successful cochlear implants were not possible in the foreseeable future. However, over the last 30 years, many of their objections have been overcome. We have learned how to partially reproduce the coding of sound with electrical stimulation; to implant the cochlea without significant damage; and to process speech so that it can be understood. Furthermore, improvements in speech perception have occurred over the last 20 years, principally because of the selection of more frequency information and its presentation on a place-coding basis.

After establishing the benefits of the cochlear implant in adults, three children were implanted in 1985 and 1986 in Melbourne. This was the start of an international trial by Cochlear Limited to determine whether the multiple-electrode cochlear implant would also benefit children who became deaf early in life or were born deaf. The trial showed that 60% of children born deaf were able to understand some open-set speech using electrical stimulation alone, and the majority had significant help in lip-reading. The U.S. Food & Drug Administration approved the device as safe and effective for children aged 2 years and older in 1990.

SUBSEQUENTLY, IN A STUDY OF CHILDREN IN MELBOURNE, BKB SENTENCE SCORES WERE COMPARED AGAINST AGE AT IMPLANTATION, AND CONSIDERABLE VARIABILITY IN RESULTS WAS FOUND (SEE FIG. 1). HOWEVER, A CURVE FITTING OF THE DATA EMphasized THAT THE RESULTS WERE BETTER IN YOUNGER CHILDREN, AND, IF EXTRAPOLATED BACK, COULD HAVE BEEN EVEN BETTER IF THE CHILD WAS IMPLANTED BEFORE 2 YEARS OF AGE (FIG. 1).

Before deciding to perform surgery in children younger than 2 years, a series of biological studies were necessary to ensure that surgery on children this young was safe. Children younger than 2 years present special surgical problems, including the effects of head growth, the possibility of inner ear complications from otitis media, which is prevalent in this age group, and the effects of electrical stimulation on the developing nervous system. This research was part of a special 5-year contract with the U.S. National Institutes of Health, and the results showed no cause for concern for surgery in young children.

SPECIFIC CHALLENGES FOR THE THIRD MILLENNIUM

There are a number of challenges facing cochlear implantation in the Third Millennium to further improve its performance and extend its benefits to as many people who are hard-of-hearing as possible.

TO PROVIDE BETTER REPRODUCTION OF THE CODING OF SOUND

Research is already contributing answers to this question. Electrical stimulation has helped to support the view that the temporal coding of frequency is not accomplished simply through the timing of responses in single fibers, but through the timing in a group of fibers. Although the individual nerves fire in phase with the sound waves, they do not fire each cycle. Conversely, the population as a whole fires each cycle.

Specifically, the frequency coding depends on the convergence of a group of fibers onto individual brain cells. The brain cell may identify the frequency of the sound by using a time window in which the right number of appropriate spike intervals must arrive to make the cell fire (Fig. 2). To achieve this fine temporal and spatial pattern of responses, a new electrode array will be required with many more electrodes to stimulate small groups of auditory nerve fibers, as illustrated in Fig. 3.

This array should enable the responses to the rapid phase changes in basilar membrane vibration to be reproduced. Figure 4 shows the phase changes that occur at the site of maximal vibration. The neural responses to these phase changes may be very important for frequency coding (Fig. 4).
To further improve the perception of speech and other sounds in noise

The improvements in speech processing in quiet already have resulted in better speech perception in noise. Figure 5 shows mean CUNY sentence scores of 90% for the SPEAK strategy in quiet and 60% at a 10dB signal-to-noise ratio. However, a 100% score at a 0dB signal-to-noise ratio would be normal (Fig. 5).

Further improvements in speech perception in noise have been achieved using the Griffiths/Jim adaptive beam-forming technique and two microphones. The Griffiths/Jim beam former uses an adjustable filter to annul the noise. It works well for a single noise source, but can break down in a reverberant field.

The SIT sentence results for the Griffiths/Jim beam former with four cochlear implant patients using the SPEAK strategy are shown in Figure 6 (2). In quiet, the mean scores for the beam former and the control were 83%, and 84%, and in noise at a 0dB signal-to-noise ratio, 43% for the beam former and 9% for the control. However, the results for this and other beam formers still do not give results that are comparable to normal.

Improved perception in noise should be possible by better reproduction of the mechanisms used by the brain. Physiologic research shows that binaural neural processing is very sensitive to phase differences between each ear, and this is critical for signal detection in noise. As shown in Figure 7, the mechanism for this is a series of delay lines and coincidence detectors.

Replication of this mechanism electronically could provide better results. Until now, it has been difficult to reproduce the parallel processing in the brain by electronic means, but this will improve with the development of better electronic neural networks.

To develop a totally implantable cochlear implant

Making the cochlear implant unable to be seen by others could be important. Teenagers are very sensitive about their deafness and may not use their device in company. This would mean implanting the speech processor and the microphone in the body.

Some have approached the problem by implanting an electret microphone under the skin behind the ear or, more recently, under the skin of the ear canal. A piezoelectric microphone has also been developed for implanting under the skin of the ear canal. Because these approaches have inherent difficulties of frequency response and extrusion, sensors of tympanic membrane and
ossicle vibrations are being developed, including a piezoelectric bimorph cantilever, accelerometer, and the fiberoptic lever system being researched at the University of Melbourne.

The fiberoptic lever system detects the ear drum vibrations through the modulation of light intensity. The device has a sensitive membrane coupled to the ear drum, and an optical fiber bundle directs a laser beam at this vibrating membrane. The vibrations cause the laser intensity to fluctuate. These fluctuations are reflected and picked up by the implanted photo detector electronics, then converted to a code for stimulating the auditory nerve. The sensor would be placed in the middle ear, and all the electronics and the rechargeable battery would be placed in the mastoid process.

To use nerve growth factors to protect the hearing nerve from dieback after deafness

Research using nerve growth factors or neurotrophins may lead to better results with the cochlear implant with more nerves to stimulate, and, ultimately, the pharmacologic cure of sensorineural hearing loss. We have begun research in this area to determine the best combinations and doses of neurotrophins to use. The results of some of our first research studies on cultures of rat spiral ganglion cells are shown in Figure 8 (3). There was considerable improvement in survival when neurotrophin NT-3 was used in combination with neuronal cytokine transforming growth factor TGF-3.

There are a number of possible ways to deliver the neurotrophin to the site of action, including a micropump, slow release from polymers, and viral vectors. To test the use of different combinations of factors in vivo, we have been injecting them into the inner ear with a micropump.

Not only could these nerve growth factors protect the auditory nerve from dieback, but they could cause the auditory nerve and hair cells to regenerate, which may ultimately represent the pharmacologic cure of sensorineural deafness.

To reestablish auditory plasticity to help implanted children achieve optimal speech perception

This research will initially aim at overcoming defects in temporal and place coding of frequency and defects in the perception of speech elements by specific training at these levels. We have begun research in this area and have found that some children with poor speech perception have good electrode place discrimination but cannot distinguish between the formants required for vowel recognition.

Vowels are coded by the first and second formant frequencies. With speech processing strategies, the formants in vowels are represented by two places of stimulation within the cochlea. Therefore, the formants of vowel pairs...
have varying electrode separations, as illustrated in Figure 9. We have calculated an index for assessing the spatial separation of electrodes representing the formants in vowel pairs. The index was calculated as the lengths of vectors in a Euclidean space. The distance between a pair of vowels was the square root of the sum of squares of the first and second formant electrode separations. The indices for some selected vowel pairs are shown in Figure 9.

An initial study was performed in five children with poor speech perception but good electrode place discrimination to train them in formant discrimination if this was poor (4). It was hoped this would lead to better speech perception. Figure 10 shows some of the results from one of the two children who significantly benefitted from the training. This child had an electrode difference limen of 2. On the top left are the results for the hid/hod discrimination, which had a formant separation index of 10.2. Because this was considerably greater than the electrode difference limen of 2, there were good results before and after training. Conversely, for the vowel discrimination had/hod on the top right, the formant electrode separation index was 7.1, and the vowel distinction could only be made after training. Similarly for the vowels hud/hod with a separation index of 2.8, the training was successful. The training of these and other vowel combinations carried over to the perception of words as shown on the lower right in Figure 10.

Secondly, in those children for whom the critical period for plasticity has passed, it may be possible to use neurotrophins to facilitate a return of the plasticity required to develop the neural connections for the coding of the frequencies needed for speech perception.

As illustrated in Figure 11, the neurotrophin would be released from the cochlear implant electrode. The neurotrophin would pass to a receptor site on the synapse between the auditory nerve fiber and cochlear nucleus cell, which would facilitate the release of transmitters across the synaptic cleft. These would activate a signal cascade of proteins in the cytoplasm that would reactivate the gene for the neurotrophin. Messenger RNA for the protein would be

\[ \text{FIG. 11. A diagram of a cochlear implant electrode releasing a neurotrophin that would reactivate the production of neurotrophin along the auditory pathway to establish the neural connections required for frequency coding.} \]
transcribed and then translated into the neurotrophin in the cytoplasm. The release of the neurotrophin would not only facilitate further transmitter release, but would cause the neural sprouting required for the coding of sound to reestablish auditory plasticity. The neurotrophin produced in the cochlear nucleus would also propagate to higher auditory centers, establishing appropriate neural connections along the auditory pathways.

CONCLUSION

In the Third Millennium, a better understanding of how the brain codes sound, increased knowledge of the molecular biology of the brain, a greater understanding of speech perception, and advances in applying this knowledge to cochlear implants holds out hope that most profoundly deaf people should be able to communicate almost normally.

REFERENCES
