

POTENTIAL AND LIMITATIONS OF COCHLEAR IMPLANTS IN CHILDREN

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INTRODUCTION

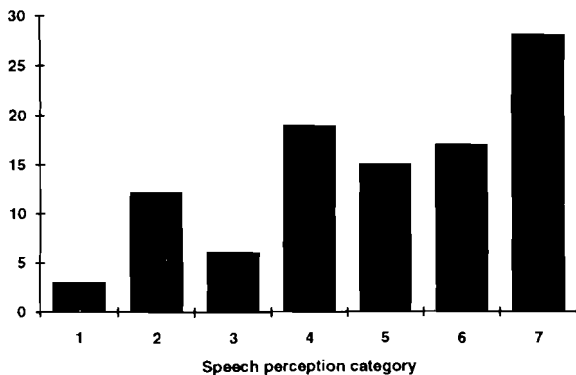
Multiple-channel cochlear implants have been in use with children and adolescents for 8 years. The speech perception, speech production, and language of many of these children has been investigated in some detail.¹⁻⁴ There have been many predictions about factors that may affect the performance of children with implants. For instance, it has been suggested that children with a congenital loss of hearing would not have the same potential to benefit from a cochlear implant as those with an acquired loss. Similarly, it has been suggested that younger children are likely to gain more benefit from a cochlear implant because of the effect of various critical ages for language learning.⁵ As more results have become available, it has been our observation that the performance of any particular child with a cochlear implant does not appear to follow well-defined rules, and that generalizations about the potential of certain groups of children are likely to encounter many exceptions. We now have a large quantity of results for children using cochlear implants, and it may be possible to determine some of the factors that have a significant effect on performance. This paper will attempt to identify some of these factors by reviewing speech perception results for 100 children implanted with the Nucleus 22-channel cochlear prosthesis in Australia and speech perception results for adult patients. This analysis will use an "information processing" model of a child using a cochlear implant. That is, we will assume that a child will benefit from a cochlear implant in terms of speech perception, production, and language development, if he or she receives a maximal amount of auditory information from the environment, and is able to process this information successfully. This model divides potential limiting or predictive factors into those that affect the information presented to the auditory system (eg, implant technology,

surviving auditory neurons) and those that affect the processing of this information (eg, development of central auditory pathways, amount and consistency of auditory input).

METHOD AND RESULTS

The most recent speech perception results for all children and adolescents (up to 19 years of age) implanted in Melbourne and Sydney before January 1993 were tabulated, and each child was placed into one of seven hierarchic categories of speech perception performance. This resulted in a total of 100 children and adolescents in the study. This categorization of results provides a way of looking at the performance of children across age groups. It is not possible to use the same tests across all ages, but it is almost always possible to determine whether a child is consistently demonstrating a particular perceptual skill from available test results. In addition, the range of performance observed across children using cochlear implants is large, and no particular test can provide a suitable measure of speech perception that covers this range. The categories used were arrived at after consultation with clinicians and were based in part on other categorizations used for speech perception results in children.^{2,6} The seven categories were as follows:

1. Detection of speech sounds only.
2. Discrimination of suprasegmental aspects of speech in addition to 1.
3. Discrimination and recognition of vowels in addition to 1 and 2.
4. Discrimination and recognition of consonants in addition to 1 through 3.
5. Minimal open-set speech perception in addition to 1



Categorization of speech perception performance for 100 children using multichannel cochlear implants (see text for explanation of speech perception categories).

through 4.

6. Open-set speech perception (>20% phoneme score for PBK words).
7. Good open-set speech perception (>50% phoneme score for PBK words).

Children were categorized on the basis of at least two speech perception test scores that indicated significantly above-chance performance in the appropriate skill. The most commonly used assessments were a number of subtests from the PLOTT battery,⁷ the NU-CHIPS closed-set test,⁸ and the PBK monosyllabic word test.⁹ The number of children falling in each category is shown in the Figure. This shows that 60% of the children have some open-set speech perception ability and that approximately 30% are able to recognize more than 50% of phonemes in monosyllabic words (category 7). Conversely, 15% of the children show very limited speech perception ability (categories 1 and 2). These categories of speech perception represent a very wide range of performance. At the lower end of the scale are children who are unable to use auditory input from the implant for the most basic syllabic contrasts. In comparison, children in category 7 are generally able to communicate freely (allowing for differences in language ability) using auditory input alone. The categorized results were subjected to a multiple regression analysis with speech perception category as the dependent variable and the following preoperative and postoperative parameters as independent variables:

1. Age at time of implantation in years (AGE).
2. Duration of profound hearing loss in years (DUR).
3. Type of hearing loss: congenital or acquired (CONG).
4. Type of hearing loss: progressive or other (PROG).
5. Age at onset of hearing loss in years (ONSET).
6. Preimplant residual hearing, based on number of aided thresholds within the speech spectrum (HEAR).
7. Number of electrodes used in speech processor (ELEC).
8. Mode of stimulation (common ground or bipolar) (MODE).

9. Dynamic range for electrical stimulation (Melbourne patients only) (DYN).
10. Experience with cochlear implant use in years (EXP).
11. Educational placement after implantation: oral-aural or total communication (EDUC).

The results of this analysis indicated that age at time of implantation (AGE), whether the hearing loss was congenital or not (CONG), age at onset of hearing loss (ONSET), number of electrodes in use (ELEC), and mode of stimulation (MODE) were not associated with improved speech perception performance to a significant extent in this group. In addition, the dynamic range for electrical stimulation was not significantly associated with improved speech perception performance for the Melbourne patients ($n = 48$).

The duration of profound hearing loss (DUR) showed a highly significant ($p < .001$) negative association with perceptual category. Progressive hearing losses (PROG) were associated with better perceptual performance ($p < .01$), as was useful preimplant residual hearing (HEAR; $p < .001$). Experience (EXP) with the implant also showed a highly significant ($p < .001$) positive association with perceptual category, and an oral-aural educational placement (EDUC) was associated with better performance ($p < .05$). These five variables, when included in a linear multiple regression analysis, accounted for 37% of the variance in the speech perception results. The regression equation associated with this analysis was as follows:

$$\text{Speech perception category} = 3.3 - 0.14 \text{ DUR} + 1.9 \text{ PROG} + 0.7 \text{ HEAR} + 0.42 \text{ EXP} + 0.87 \text{ EDUC}$$

DISCUSSION

The equation obtained from the regression analysis can be interpreted in the following way. On average, a profoundly deaf child or adolescent will be expected to discriminate vowel sounds immediately after implantation (category 3). If the child has been profoundly deaf for a considerable time, this initial ability may be reduced. If the child has had a progressive hearing loss or has useful residual hearing prior to implantation, initial speech perception ability may be considerably better. We may also expect perceptual ability to improve slowly with experience (approximately one category for every 2 years, on average). Additionally, children in an oral-aural educational program may be expected to show slightly better performance on speech perception assessments. However, it is clear that children with better speech perception, with more residual hearing prior to implantation, or with progressive hearing losses are more likely to be in an oral-aural or integrated educational setting. Thus, the finding that this type of setting is associated with better speech perception may be circular in some ways. It does not provide clear evidence that a particular educational environment is preferable for all implanted children.

Having proposed an interpretation of these statistical results, we should note that this regression analysis accounts for less than 40% of the variance in the categorical speech perception data. This implies that speech perception in children with cochlear implants is inherently unpredictable and/or that there are factors not included in this analysis that have

an important effect on speech perception performance. Clinical experience suggests that one of these factors may be the child's home environment. It is well established that this plays an important role in educational progress for hearing-impaired children.⁶ On the other hand, it is difficult to know how to obtain an objective assessment of such factors to enable inclusion in a statistical analysis of results. Another major factor may be additional handicaps, which are relatively common among profoundly deaf children. These are difficult to measure, particularly when a cognitive deficit is suspected, as many assessment tools are dependent on language development, which is likely to be delayed due to the hearing loss.

It is interesting to note that there was no significant difference in speech perception performance found between children with a congenital hearing loss and those with an acquired loss. There was also no significant effect for age at onset of hearing loss or for age at implantation. These findings are somewhat at odds with predictions about children using cochlear implants, as it would seem reasonable to expect that younger children would learn to use the cochlear implant more effectively, and that those with a congenital loss would have more problems. However, in this group of children, most of the acquired losses are due to meningitis at or before the age of 2 years and could be classed as "prelingual" deafness. Thus, we are comparing those with congenital losses with a group of mostly early-deafened children, and this may explain the result. When we compare the small group of children with progressive losses (8) with the rest, there was a significant difference. These children all became profoundly deaf after the age of 4 years and could be classed as "postlingually" deafened. Thus, the expectation that postlingually deaf children will perform better than prelingually deaf children with cochlear implants is supported by these data, although the proportion of postlingually deaf children in the sample is quite small.

The lack of a significant effect for age is also unexpected, but a related effect is seen within the duration of profound deafness variable. Approximately 70% of this group were congenitally deaf. For these children, the duration of deafness is the same as their age at implantation. Thus, there appears to be a strong effect of age at implantation for the congenitally deaf children. Younger congenitally deaf children tend to perform better on speech perception tasks. For those with acquired deafness, the situation appears more complicated and may depend more on the duration of profound deafness than on age. We are now in a position to review these results in terms of the information-processing model suggested in Introduction.

FACTORS AFFECTING INFORMATION PRESENTED TO AUDITORY SYSTEM

Implant Technology. It is clear that our ability to control electrical stimulation of the auditory nerve is improving, as is the knowledge of the physiology of the peripheral and central auditory systems. The main advances in cochlear implants have been the development of multichannel devices, improvement in the fine control of stimulation parameters, and the increase in the rate at which stimulation parameters can be changed. At a more practical level, implants for children must be small and reliable, and continuing improvement is likely in

this area. Thus, there appears to be no doubt that implant technology will be able to provide an increased amount of information to the auditory nerve in the future.

Surgical Result. Current cochlear prostheses require an electrode array to be placed at a suitable location for stimulation of the auditory nerve, usually within the cochlea. As we are always dealing with pathologic ears, there is the possibility that damage or malformation of the cochlea may affect our ability to stimulate the nerve. This is particularly relevant in children in whom the cause of deafness is meningitis and new bone growth within the cochlea is common. More generally, it has not been possible to insert electrodes into the apical turn of the cochlea. It is likely that improved electrode arrays and surgical techniques will enable more effective stimulation of the auditory system in the future, although there will always be some limitations imposed by the degree of damage to the cochlea in particular cases.

Surviving Auditory Neurons. It is assumed that the proportion of surviving auditory neurons in the cochlea of profoundly deaf patients limits the amount of information that can be transferred to the auditory system. This is a factor in the application of cochlear implants over which we have little control. A review of adult results¹⁰ suggests that the patients who show good perceptual skills at their preoperative promontory stimulation test and have larger dynamic ranges for electrical stimulation perform significantly better on open-set speech perception. These measures may reflect surviving neural populations, although there is no direct evidence to support this suggestion. In any case, there may be little that can be done to change the amount of surviving neurons. However, electrical stimulation of the nerves by a cochlear implant may prevent further deterioration of neural elements.¹¹

Speech-Processing Scheme and Technology. There has been a rapid improvement in the speech perception ability of adult patients using cochlear implants over the last 10 years. This has been at least partly due to improvements in speech-processing schemes and their implementation. Results for all adult patients implanted in Melbourne (tested 4 to 6 months after implantation) show significant improvements corresponding to the main changes in speech processing that have been implemented for the Nucleus device. The mean results for open-set sentence recognition are F0F2 16%, F0F1F2 38%, Multipeak 59%, and Speak 87%. There is no reason to believe that this trend will not continue, and we can expect that children with implants will receive more useful auditory information in the future.

Individual Programming of Device. Modern multichannel implants require a number of psychophysical measurements to be made to allow the prosthesis to operate effectively. These include thresholds and comfort or discomfort levels for each electrode and could include other parameters such as loudness growth assessment. In the extreme cases of poor programming, it is possible that a child may be obtaining no useful information from a cochlear implant system (for instance, if all maximum levels are set below the subjective thresholds). The programming of the device is an important issue in young children, as reliable psychophysical measure-

ments are difficult to obtain in this group. Progress has already been made in this area, with the use of various objective techniques to assist with programming in young children, and expertise is likely to continue to improve.

FACTORS AFFECTING SUCCESSFUL PROCESSING OF AUDITORY INFORMATION

Development of Auditory Pathways. Physiological studies have suggested that the central auditory pathways of young animals deprived of auditory input do not develop in a normal fashion.¹¹ This may have profound significance for cochlear implantation in children. However, some congenitally profoundly deaf children (11 in this group) are demonstrating speech perception skills equivalent to those of postlingually deaf adults (category 7) after some years of experience with a cochlear implant. It seems that any failure of the central auditory pathways to develop due to a congenital hearing loss may be of little consequence in these children when other factors are favorable.

Critical Ages for Speech-Language Development. It appears likely that these critical age ranges exist and may limit the use of auditory information for speech and language development for older implanted children. However, the trend is already evident toward implantation of younger children, and implant technology, surgical techniques, and audiologic assessment are busy keeping pace with the associated problems. In the future, it is likely that most children will be implanted early, or soon after developing a hearing loss, and that the problems of critical ages may become less relevant.

Sensory Deprivation. There is strong evidence that sensory deprivation is an important factor in speech perception results with cochlear implants. Longer periods of deafness are associated with poorer speech perception in studies of adult patients¹⁰ and in the present study of children. This effect should be reduced in the future, as most children and adults will be implanted soon after developing a profound hearing loss.

Amount and Consistency of Auditory Input. From the results of this study, it is clear that children using cochlear implants improve with experience. It is reasonable to assume that the quality of this auditory experience is likely to be important in their progress. The auditory input provided by an implant is only available as long as the speech processor is switched on, batteries are not flat, cables are not broken, and the correct settings are used. Clinical experience suggests that there is large variability in the amount of time that young children actually have their system operating correctly. This, in turn, is determined by the ability and/or motivation of parents, teachers, and clinicians to monitor these potential problems consistently. If we assume that the cochlear implant is working, then there are large variations in the amount of meaningful auditory input that may be provided in the home or (pre)school environment. Again, it is worth taking an optimistic outlook that the habilitation of children using cochlear implants will improve with experience and that the factors mentioned above will not play as great a part in eventual outcomes.

Other Handicaps. This is often a controversial area, as cochlear implants may potentially offer false hope to families

of multiply handicapped (including deafness) children when cognitive or other central deficits may prevent a useful result. It is important to attempt to better understand the additional disabilities that may be present along with profound deafness and to devise better ways of assessing such problems.

CONCLUSION

Having discussed five factors limiting the information presented to the auditory nerve and five factors that may limit the successful processing of this information, there are many reasons to be optimistic about the future of cochlear implants in children. Implant technology, surgical techniques, speech processing, and programming of the implant devices are almost certain to improve, leaving neural survival within the cochlea as perhaps the main limiting factor in providing information to the peripheral auditory system. Similarly, many of the factors, such as sensory deprivation, that appear to limit the ability to use auditory information effectively will be reduced in their impact as the trend to implant younger children continues. It also seems likely that our understanding of the optimal auditory environment for implanted children will improve, providing the opportunity for a greater proportion of children to develop good open-set speech perception. Additional handicaps will continue to cause some problems for implanted children; however, it is probable that most children implanted in the future will have the potential to reach a level of speech perception that will allow language development through audition.

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