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Speech perception in children using cochlear implants: prediction of long-term outcomes

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ABSTRACT *A group of 102 children using the Nucleus multichannel cochlear implant were assessed for open-set speech perception abilities at six-monthly intervals following implant surgery. The group included a wide range of ages, types of hearing loss, ages at onset of hearing loss, experience with implant use and communication modes. Multivariate analysis indicated that a shorter duration of profound hearing loss, later onset of profound hearing loss, exclusively oral/aural communication and greater experience with the implant were associated with better open-set speech perception. Developmental delay was associated with poorer speech perception and the SPEAK signal coding scheme was shown to provide better speech perception performance than previous signal processors. Results indicated that postoperative speech perception outcomes could be predicted with an accuracy that is clinically useful.*

Keywords: deafness, cochlear implant, hearing-impaired children, speech perception, predictive factors

Introduction

The use of multiple electrode cochlear implants in hearing-impaired children is now firmly established as a safe and effective means for improving auditory detection and discrimination when benefit from conventional amplification is limited (Staller et al., 1991; Tyler, 1993; Geers and Moog, 1994; Waltzmann et al., 1994; Osberger, 1995; Dowell and Cowan, 1997; Svirsky and Meyer, 1999). A primary goal of cochlear implantation is to enable a child to use these improved auditory abilities for the comprehension of speech and for developing spoken language (Tobey and Hasenstab, 1991; Dawson et al., 1995; Tye-Murray et al., 1995; Serry and Blamey, 1999).

The development of functional spoken language would be considered by most clinicians, teachers and parents, to be a major long-term aim of the cochlear implant procedure (Geers and Moog, 1994). It is clear, however, that a properly functioning cochlear implant does not guarantee this outcome (Dowell et al., 1995; Miyamoto et al., 1994). The detection and discrimination of sound does not ensure that a child will be able to assemble the complex stream of auditory information in connected speech into meaningful language. In addition, improved auditory discrimination ability does not necessarily imply that the finely coordinated motor control necessary for intelligible speech will develop.

On the other hand, it is reasonable to assume that the perception and comprehension of speech is an important ingredient in the development of spoken language and that measures of speech perception will have some relationship to speech and language abilities (Geers and Moog, 1987). The measurement of speech perception also provides direct evidence of the assistance provided by the cochlear implant system (Dowell and Cowan, 1997). This paper will focus on the results of speech perception assessments on children using multichannel cochlear implants and consider the influence of a number of the children's individual characteristics on their ability.

The analysis of the speech perception results will be interpreted in terms of predicting long-term speech perception performance from preoperative factors. This may provide useful information for counselling families considering cochlear implantation for their child

Method

Subjects

The children in this study included all children who underwent cochlear implant surgery at the Melbourne Cochlear Implant Clinic between 1986 and 1998, with some exceptions. The exceptions included those under 4 years of age at September 1999 who did not have formal speech perception results, and three children who moved away from the Melbourne area before formal speech perception testing took place. This left a total of 154 children implanted in Melbourne with formal speech perception results available. Each child was assessed at approximately six-monthly intervals after implantation. The battery of speech perception tests included closed-set vowel imitation (Dawson, 1991; Dettman et al., 1995), closed-set monosyllable recognition (Plant, 1984), the open-set Phonetically Balanced Kindergarten (PBK) words (Haskins, 1949), the NU-CHIPS closed-set consonant discrimination test (Elliott and Katz, 1980) and the open-set Bench–Kowal–

Bamford (BKB) sentence test (Bench et al., 1979). The exact set of tests used at a particular session varied depending on the age, cognitive abilities and cooperation of the child. This paper will consider only open-set speech perception results for word and sentence material that were available on 102 children, all those over 4 years of age at September 1999. Table 1 shows demographic details for these children.

Speech perception assessments

Children were assessed using the open-set PBK words and open-set BKB sentences at approximately six-month intervals following their cochlear implantation. Test sessions for children under 6 years of age were conducted using live voice by an audiologist or speech pathologist experienced in speech perception assessment. All testing was carried out using audition alone, with visual cues including lip-reading and sign unavailable. Older children were assessed, where possible, using recorded material. Live-voice sessions were video-recorded and scored independently by two audiologists or speech pathologists with experience in transcribing the speech of hearing-impaired children. Differences of more than 5% between the two scorers would then involve a third scorer. The final score was the mean of the two scores in closest agreement.

There are three PBK word lists available containing 50 words each. The PBK words were scored on the basis of number of words correct and number of phonemes correct. The PBK word lists contain between 155 and 158 phonemes, including some consonant clusters.

Table 1: Demographic information for the 102 children using the Nucleus multichannel cochlear implant involved in this study

	Mean	Median	s.d.	Min	Max
Age at implant (years)	5.9	4.5	4.4	1.5	17.6
Age at onset of profound loss (years)	1.4	0.0	3.3	0.0	16.9
Duration of profound loss (years)	4.6	2.9	4.1	0.4	17.6
Experience with implant (years)	4.0	3.6	2.7	0.3	10.3
Type of profound hearing loss		*n*			
Meningitis		17			
Congenital		70			
Progressive		15			
Post-implant communication mode		*n*			
Exclusively oral/aural		61			
Manual supplement		41			
Developmental delay		*n*			
Developmental delay confirmed		10			
No confirmed developmental delay		92			

There are 20 lists of BKB sentences modified for Australian usage. These contain 16 sentences scored on the basis of 50 key words per list (three or four words per sentence).

The video-recording of test sessions was considered desirable to reduce any bias that may be introduced in the presentation or scoring of the assessments by a single tester. These potential problems are partially avoided by the use of recorded material. However, clinical experience has suggested that a successful assessment of a young child will be more likely in the live-voice situation (Tyler, 1993). The use of recorded material does not resolve the problem of poor speech production when spoken responses are required from the child.

Additional subject information

The following additional information was collected for each child and coded into four interval variables and five binary categorical variables. The predictor variables were chosen after consideration of the existing studies on factors affecting cochlear implant outcomes for children (Miyamoto, 1994; Dowell et al., 1995, 1997; Cowan et al., 1997; Snik et al., 1997; Archbold et al., 1998; Hodges et al., 1999; Nikolopoulos et al., 1999; Pyman et al., 1999; Sarant et al., 2000; Waltzmann, 2000).

Interval variables

AGE – age at the time of implantation.
ONSET – age at onset of profound hearing loss.
DUR – the duration of profound hearing loss prior to cochlear implantation.
EXP – experience in years with the cochlear implant.

Binary categorical variables

MEN – whether the hearing loss was due to meningitis, 1 = yes, 0 = no.
PROG – whether the hearing loss was progressive in nature, 1 = yes, 0 = no.
COMM – whether the child used an exclusively oral communication mode in the first two years after cochlear implantation, 1 = oral, 0 = manual supplement.
DEL – whether there was documented evidence of developmental delay; 1 = yes, 0 = no.
STRAT – the signal coding used at the time of assessment, 1 = SPEAK, 0 = Multipeak.

Statistical analysis

As these variables were to be used as predictors in a multiple regression analysis, the covariance of the variables was investigated using a principal component analysis. This indicated that only seven of the nine specified variables contributed independently to the variance across the group. These could be related directly to AGE or DUR but not both, ONSET or PROG but not both, MEN, COMM, DEL, EXP and STRAT. The principal component analysis identifies variables that have significant correlations. The use of highly correlated predictor variables within a multiple regression analysis is inappropriate. DUR and ONSET were used in subsequent analyses rather than AGE and PROG.

The seven, uncorrelated predictor variables (AGE, ONSET, EXP, COMM, STRAT, MEN, DEL) were then used in step-wise multiple linear regression analyses with PBK word scores, PBK phoneme scores and BKB sentence scores as the dependent variables. Regression equations were then determined for the significant predictor variables.

Results

Step-wise multiple regression analyses

PBK phoneme scores

This analysis included 318 test scores obtained from 102 children at times ranging from three months to 10 years post-implant. Duration of profound deafness, age at onset of profound hearing loss, post-implant communication mode, speech-processing strategy, experience with the cochlear implant and developmental delay were shown to have significant predictive value for PBK phoneme scores. In all, these six variables accounted for 52% of the variance in phoneme scores. The regression equation derived from this analysis was:

$$\text{PBK (phoneme score)} = 7.24 + 18.8*\text{STRAT} + 17.5*\text{COMM} - 1.97*\text{DUR} + 1.88*\text{EXP} - 7.43*\text{DEL} + 0.893*\text{ONSET}. \tag{1}$$

All variables were significant at the 0.001 level except for DEL and ONSET, which were significant at the 0.05 level. Of the individual subject characteristics, postoperative communication mode accounted for the largest proportion of variance in the data (18%). Duration of profound deafness and implant experience each accounted for around 5% of the variance. Age at onset of profound hearing loss and developmental delay accounted for only small proportions of the total variance. The accuracy of prediction of PBK phoneme scores from the regression equation was assessed by considering the distribution of residuals (predicted minus actual scores). The distribution of residuals followed an approximately normal distribution with standard deviation of 17%. Predicted scores from the regression equation were within ± 25% of actual scores in 86% of cases.

PBK word scores

This analysis also included 318 test scores obtained from 102 children at times ranging from three months to 10 years post-implant. Duration of profound hearing loss, age at onset of profound hearing loss, post-implant communication mode, speech processing strategy, experience with the cochlear implant and developmental delay were shown to have significant predictive value for PBK word scores. In all, these six variables accounted for 37% of the variance in word scores. The regression equation derived from this analysis was:

$$\text{PBK (word score)} = -14.9 + 15.6{*}\text{STRAT} + 13.2{*}\text{COMM} - 1.09{*}\text{DUR} + 1.77{*}\text{EXP} - 7.18{*}\text{DEL} + 1.03{*}\text{ONSET}. \quad (2)$$

Note that this is identical in form to the regression equation for phoneme scores. These similar results are to be expected as the phoneme and word scores are alternative ways of scoring the same assessments and are thus highly correlated.

The proportions of variance accounted for by the predictor variables were similar to those reported above for the PBK phoneme scores. The distribution of residuals followed a positively skewed distribution. Predicted scores were within ± 25% of actual scores for 87% of cases.

BKB sentence scores

This analysis included 245 test scores from 80 children at times ranging from three months to 10 years post-implant. Duration of profound hearing loss, age at onset of profound hearing loss, post-implant communication mode, speech processing strategy and developmental delay were shown to have significant predictive value for BKB sentence scores. These five variables accounted for 40% of the variance in sentence scores. The regression equation derived from this analysis was:

$$\text{BKB sentence score} = 1.56 + 27.9{*}\text{STRAT} + 6.89{*}\text{COMM} - 2.07{*}\text{DUR} - 12.1{*}\text{DEL} + 1.33{*}\text{ONSET}. \quad (3)$$

This is again similar in form to the equations for PBK words and phonemes, except that the experience variable was not significant in this case. Of the individual subject characteristics, duration of profound deafness accounted for the largest proportion of variance in this data set, with smaller proportions accounted for by age at onset of profound hearing loss, postoperative communication mode and developmental delay. The distribution of residuals followed an approximately normal distribution with a standard deviation of 23%. Predicted scores were within 30% of the actual scores for 80% of cases.

Clinical significance of predictor variables

Figures 1–6 illustrate the effect of the significant variables on PBK phoneme scores for this group of children. Each successive graph shows the residual effect of a particular variable on overall scores once the effect of previous variables has been removed. Error bars indicate ± 2 standard errors of the mean in each case. The order of treatment of the variables is based on the amount of variance that each contributes to the total variance in scores. That is, the variable that contributes the largest proportion of variance (speech processing strategy) is treated first and so on with the variable contributing the least variance (age at onset of profound hearing loss) treated last.

Signal processing strategy

Figure 1 shows the effect on PBK phoneme scores of the signal processor used with the cochlear implant system during the speech perception assessments for all children. A substantial difference is evident between the means for SPEAK and Multipeak speech processors.

Communication mode

Figure 2 shows the residual effect of post-implantation communication mode on PBK phoneme scores for children in this study. Those who used exclusively oral communication following implantation showed significantly better scores than children who used some level of manual supplement for communication.

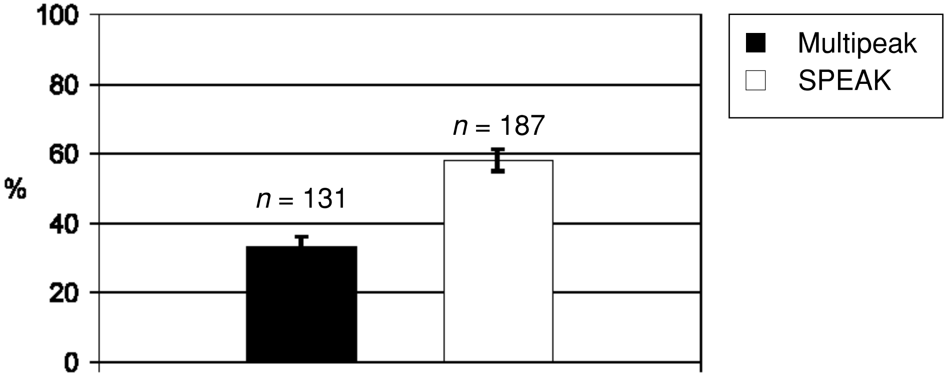

Figure 1: Mean speech perception scores for the PBK open-set word test (phoneme scores) for a group of 102 children using the Nucleus multichannel cochlear implant grouped by signal processor used at the time of testing. Error bars represent ± 2 standard errors of the mean.

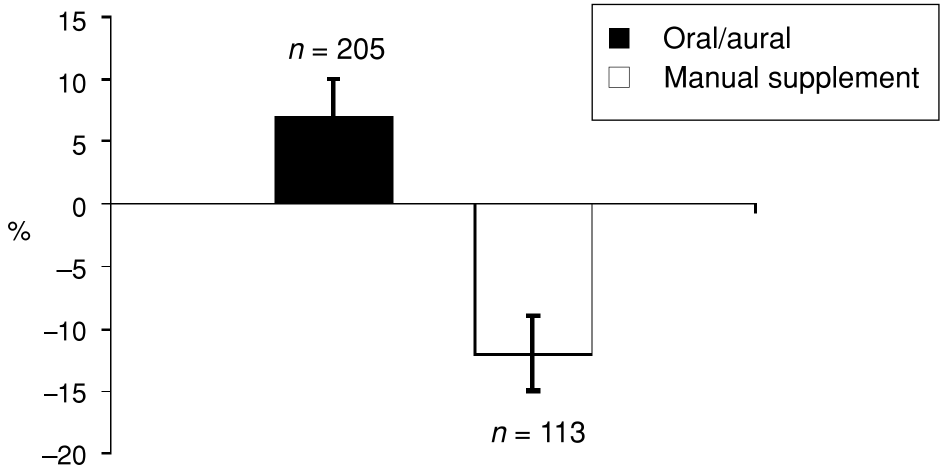

Figure 2: Mean residual PBK phoneme scores for a group of 102 children using the Nucleus multichannel cochlear implant grouped by communication mode following implantation. The effect of speech processing strategy has been removed. Error bars represent ± 2 standard errors of the mean.

Duration of profound deafness

Figure 3 shows the residual effect of duration of profound deafness on PBK phoneme scores for all children after removing the effects of speech-processing strategy and communication mode. In the case of those children with a congenital profound hearing loss, this result implies that there is significant benefit for speech perception if children are implanted earlier. In particular, children implanted before the age of 57 months (4 years 9 months) have significantly better speech perception scores than older children. Children with less than two years of profound deafness prior to implantation show the best speech perception scores in this group.

Implant experience

Figure 4 shows the residual effect of implant experience on PBK phoneme scores once the effects of speech processing strategy, communication mode and duration of profound deafness are taken into account. This analysis suggests that significant improvements are evident for speech perception performance in the first three to four years following implantation.

Developmental delay

Figure 5 shows the residual effect of developmental delay on PBK phoneme scores after removing the effects of speech processing strategy, communication

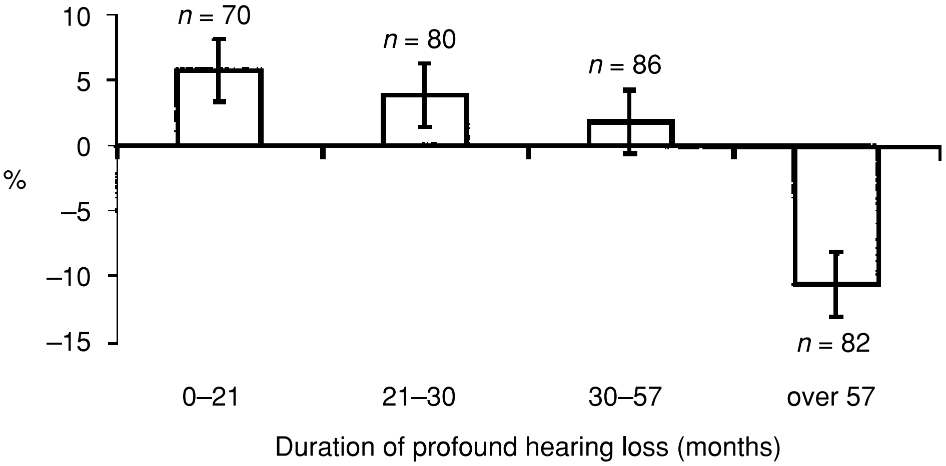

Figure 3: Mean residual PBK phoneme scores for a group of 102 children using the Nucleus multichannel cochlear implant grouped by duration of profound hearing loss in months. The effects of speech processing strategy communication mode have been removed. Error bars represent ± 2 standard errors of the mean.

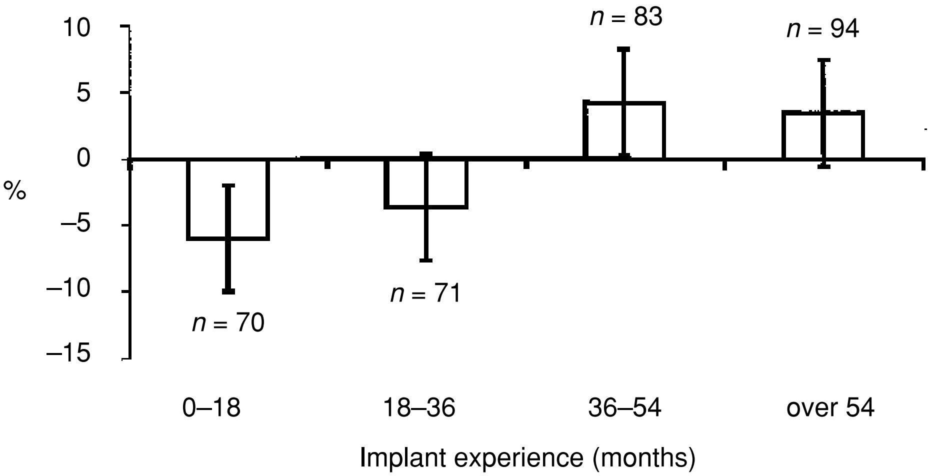

Figure 4: Mean residual PBK phoneme scores for a group of 102 children using the Nucleus multichannel cochlear implant grouped by implant experience in months. The effects of speech processing strategy, communication mode and duration of deafness have been removed. Error bars represent ± 2 standard errors of the mean.

mode, duration of profound deafness and experience. Only a small proportion of the data in this study is from children with a confirmed developmental delay, making the comparison difficult in this case. The residual results, however, do show an overall 5% decrement in PBK phoneme scores for the delayed group.

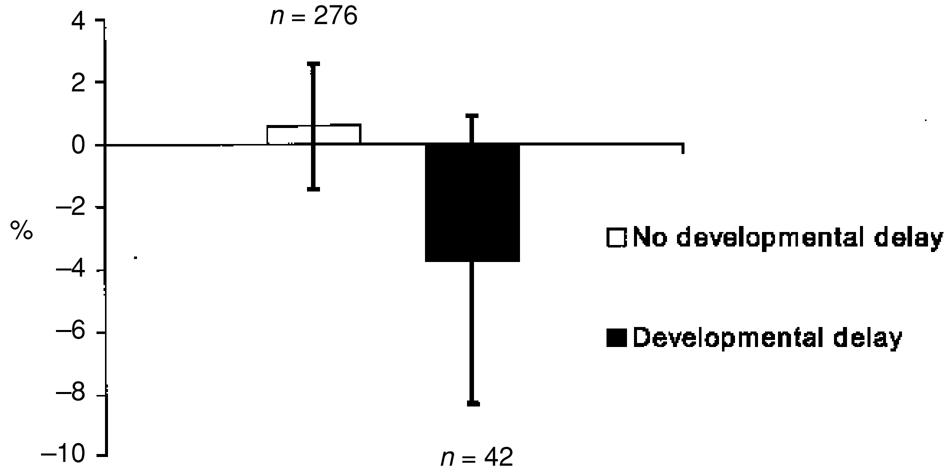

Figure 5: Mean residual PBK phoneme scores for a group of 102 children using the Nucleus multichannel cochlear implant grouped based on the presence of developmental delay. The effects of speech processing strategy, communication mode, duration of deafness and implant experience have been removed. Error bars represent ± 2 standard errors of the mean.

Age at onset of profound hearing loss

Figure 6 shows the residual effect of age at onset of profound hearing loss on PBK phoneme scores once the effects of all other significant variables are taken into account. As a large proportion of the children have a congenital profound hearing loss, the comparison here is made between unequal groups. Nonetheless, it is clear that the significant effect here is related to the group of children who became profoundly deaf after the age of 4 years. This relatively small group of children have better speech perception scores than the rest of the group even after all other variables are taken into account.

Discussion

This study indicated that most children using multichannel cochlear implants develop the ability to understand some speech in an open-set context using auditory input only. Although results for open-set speech-perception assessments varied over a wide range, we can explain a good proportion of this variance by looking at individual characteristics of the children and the signal processing used. The regression equations derived from these data can be used to predict speech-perception outcomes for young cochlear implant candidates. However, the estimates provided are accurate only within a range of ± 25–30%. Nonetheless, this is enough to assist with preoperative counselling by providing a general idea of post-implant expectations.

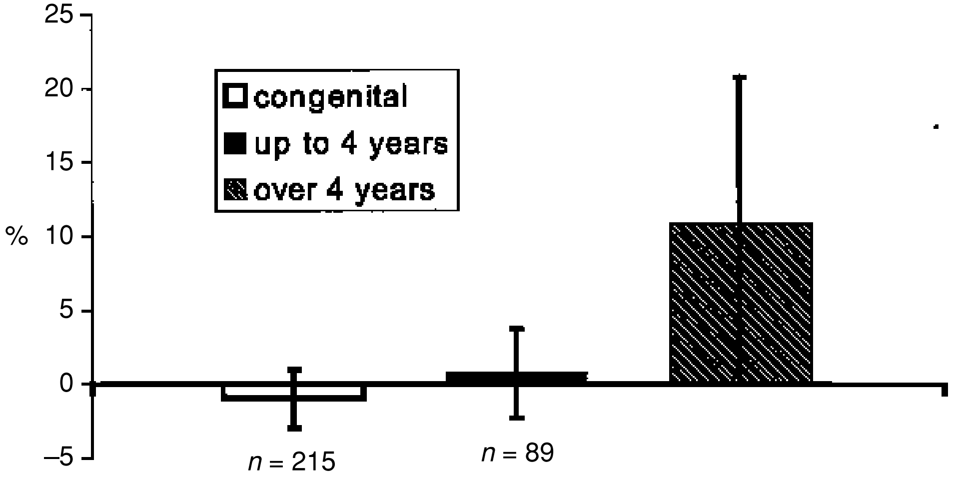

Figure 6: Mean residual PBK phoneme scores for a group of 102 children using the Nucleus multichannel cochlear implant grouped by age at onset of profound hearing loss in months. The effects of speech processing strategy, communication mode, duration of deafness, implant experience and developmental delay have been removed. Error bars represent ± 2 standard errors of the mean.

Prediction of speech-perception scores

The predictive regression equations can be simplified for clinical usage as the older signal coding (Multipeak) is no longer used, and in general we will be interested in the speech perception outcome at approximately five years post-implant. Equation (1) then becomes:

PBK(phoneme score) = 35.4 – 2*(duration of profound hearing loss) +
17.5*(communication mode) – 7.4*(developmental delay)) + 0.9*(age at onset).

For example, a 12-month-old child with a congenital profound hearing loss who is expected to use exclusively oral/aural communication and has no developmental delay, would be predicted to score 51% after five years of implant experience. In contrast, a 7-year-old child with a congenital profound hearing loss and developmental problems using sign language would be predicted to score 14% after five years. A 12-year-old child in a mainstream educational programme who has recently acquired a profound hearing loss would be predicted to score 64%, assuming no other developmental problems.

Comparison with adult results

It is of interest to note that the open-set speech-perception results for children are comparable to results for postlingually deaf adults. The significance of this comparison is that most children using implants were deafened early in life, and their ability to process auditory information has developed mostly through use of the cochlear implant input. For most adults with implants, it is assumed that the ability to process auditory information for understanding speech was developed during childhood, when they had normal or near normal hearing.

This study showed that children implanted before the age of 4 years with no significant developmental delay, and using oral communication, had mean scores of 79%, 53% and 68% for open-set phonemes, words and sentences respectively, after three to five years of experience with the cochlear implant. On similar tests of speech perception, postlingually deaf adult implant users had mean scores of 68%, 45% and 86% for phonemes, words and sentences, six months after implantation (Hollow et al., 1997). Although these data for adults and children are not directly comparable, they suggest similar performance on open-set tasks. It has been demonstrated that early-deafened children can develop the sophisticated auditory processing necessary for speech understanding through use of a cochlear implant.

Signal coding strategy

As this data set contains results across a number of years, many scores were obtained with the previous version of the signal processor for the Nucleus device. Children implanted prior to 1993 used the Multipeak signal processing strategy, with many changing to the SPEAK strategy after this date. Children implanted after 1993 used SPEAK exclusively. The results here (see Figure 1) confirm the findings of previous studies with adults (McKay et al., 1992; Skinner et al., 1994) and children (Cowan et al., 1995) that substantial improvements in speech perception have followed the introduction of the SPEAK scheme. Further work on refining both the coding strategy (e.g. the use of higher stimulation rates) and the ‘front end’ of signal processors (e.g. enhancing the dynamic range, use of noise suppression systems) is likely to lead to additional improvements in speech perception for children using implants.

Duration of profound deafness

Duration of profound deafness prior to implantation has been identified by many researchers and clinicians as an important factor in outcomes for children and adults with cochlear implants. The intuitive arguments that younger children should perform better, and the available research evidence, have driven down the average age at implantation in most clinical programmes (Dowell et al., 1995; Fryauf Bertschy et al., 1997; Miyamoto et al., 1997; Snik et al., 1997; Hodges et al., 1999; Nikolopoulos et al., 1999; Sarant et al., 2000).

This study also indicates that implantation at a younger age leads to better speech perception results for congenitally or early-deafened children. For children with acquired or progressive profound hearing loss, factors other than age may be more important. Nonetheless, it appears preferable to provide a cochlear implant as soon as possible after the onset of profound hearing loss.

Additional factors identified in this study that need to be considered for children with acquired hearing losses are the age at onset of profound hearing loss, communication mode and developmental delays. Another issue that may be important is the amount of effective use of hearing aids prior to implantation (Dowell et al., 1995; Cowan et al., 1997)

Age at onset of profound hearing loss

The age at onset of profound hearing loss has been of interest as a predictive variable since cochlear implantation in children began (Tyler, 1993). It has been clear that postlingually deafened children, where the onset of hearing loss is after 4 or 5 years of age, have an advantage over age-matched congenitally deaf children in effective use of cochlear implants. For these children, the opportunity to use hearing to develop auditory processing, speech production and language skills in the first few years of life is likely to enhance their performance with implants. Such children, however, represent a small proportion of the caseload in clinical programmes.

More commonly, children referred for cochlear implant who are not congenitally deaf have progressive hearing losses or have been deafened by bacterial meningitis within the first three years of life. In each individual case, there will be differences in the progression of hearing loss, the effective use of amplification, and opportunity for development of auditory skills and language, which may then impact on their use of a cochlear implant. The identification of onset of deafness as a predictive parameter in this study supports the view that early auditory experience enhances the ability of children to use auditory input from a cochlear implant at a later time.

Communication mode

Communication mode, as in a number of previous studies (Quittner and Steck, 1991; Dowell et al., 1995, 1997; Meyer et al., 1998, Hodges et al., 1999; Sarant et al., 2000), shows significant association with speech perception outcomes in implanted children. In the current study, only two groups of children have been identified: those who used exclusively oral communication in the years following implantation and those who used a manual supplement (sign language) in addition to oral communication. The highly significant difference between speech-perception outcomes for these groups cannot be ignored, although the cause and effect relationships remain open to interpretation.

The suggestion that the use of manual communication has a detrimental effect on outcomes for implanted children would be an over-simplification of the issues. The statistical result simply tells us that these two groups are different in some way. We must look further at why some children are using sign language before and after cochlear implantation. For those children with little or no aided hearing, families are often advised to incorporate signing into their communication to allow effective language development to take place. This may mean that the children using some sign language in this study had poorer residual hearing than the oral group. If residual hearing prior to implantation has some influence on speech perception results, then this may explain part of the difference in outcomes for these groups. On the other hand, clinical observation does not support such a difference in residual hearing for oral and total communication children in our sample.

Hearing-impaired children in exclusively oral pre-school programmes who are not making progress are often advised to consider alternative approaches, which incorporate sign language. This may mean that children in programmes using signing have been selected out of oral programmes because they do not show 'oral potential'. These children may also show slower progress in using a cochlear implant.

Finally, there may be geographical and/or socioeconomic effects at work in that hearing-impaired children will tend to access pre-school and school programmes that are in their locality. This could lead to a polarization of the children attending certain programmes based on socioeconomic factors. That is, children from poorer areas are likely to attend the local programme. If this happens to be a programme incorporating sign language, the effect of communication mode can be confounded with socioeconomic status. Socioeconomic status has been suggested to have an influence on educational outcomes for hearing-impaired children (Geers and Moog, 1987). It is the authors' observation that this type of polarization may occur in the Melbourne area.

The difficulties of untangling the many factors that may influence the preferred communication mode for an implanted child are challenging and raise issues about the relative merits of different educational approaches that have been hotly debated for many years. This study adds to the growing weight of evidence that an exclusively oral educational approach may be desirable for many children using cochlear implants. In practical terms, however, many implant candidates will benefit from a manual supplement to their communication, and this will also be important in the post-implant period. On the other hand, based on the current findings, educational programmes for implanted children should include a strong auditory/oral component. The decision by a family to proceed with cochlear implantation should, by implication, be a decision to promote the development of auditory skills in an appropriate way for each individual child.

Developmental delay

Children with developmental delay pose particular problems for cochlear implant clinicians. It is generally accepted that additional problems, particularly those involving cognitive deficits, will have an impact on outcomes with a cochlear implant (Pyman et al., 2000). On the other hand, when a child is a candidate for implantation on audiometric grounds, it is difficult to be sure when additional handicaps reach a level where cochlear implantation should not proceed. This study suggests that developmental delay can have a detrimental effect on outcomes but that these children can benefit, in terms of speech perception ability, from use of a cochlear implant. Further study is warranted to investigate the types of additional handicaps, syndromes or pathologies that are associated with particularly poor results. The assessment of multiply handicapped deaf children from an educational psychology perspective may offer insights into individual cases and assist with counselling.

Technological, peripheral and central factors

This study has demonstrated that speech perception outcomes can be predicted with a certain degree of confidence based on information obtained prior to cochlear implantation. How can these results be interpreted to lead to a better understanding of the application of cochlear implants in children? The author has used a conceptual framework in the past (Dowell et al., 1995), which may also be useful here. It is possible to differentiate between factors that affect the information provided by a cochlear implant system to the peripheral auditory system of a child, and those that affect the analysis and effective use of this information by the child. In the former category, are technological factors relating to the cochlear implant system and signal coding scheme, electrode array, surgical placement of the array in the cochlea, and the distribution and density of surviving auditory nerve cells within the cochlea. The latter group includes the status of the child's central auditory pathways, language development, auditory processing, cognitive skills, motivation and opportunity for learning. Most of the significant variables identified in this study, including age at implantation, age at onset of deafness, communication mode, experience and developmental delay, are likely to affect the ability of a particular child to use auditory information. Only the signal-coding strategy has a direct effect on how much information is presented to the child's peripheral auditory system.

Language development and speech perception

Recent data from Blamey et al. (1998) indicate a strong relationship between general language skills and speech perception for hearing-impaired children using cochlear implants and hearing aids. The results for the current study can also be interpreted in terms of a model where language skills are an underlying major factor in speech-perception progress. Further investigation is needed to look at language development for these children and its relationship to speech perception results. It is likely that cochlear implantation alone will not guarantee that a child will develop good auditory communication skills. The provision of the right environment for encouraging the development of auditory language skills appears to be crucial to a successful outcome even if children are implanted at an early age.

Conclusion

This study has identified an array of factors that have significant relationships to speech-perception outcomes for children using cochlear implants. Improvements in hardware and, in particular, the signal coding in implant systems have led to better speech perception in children, as it has for adults. In this analysis of 563 individual speech-perception assessments on 102 children, the post-implant communication mode had a highly significant association with performance, that is children using exclusively oral/aural communication demonstrated better open-set speech perception. Earlier implantation for children with a congenital profound hearing loss appeared to provide improved potential for developing speech perception. For children with acquired profound hearing loss, the age at onset and duration of deafness were important. Speech perception improved steadily with implant experience but developmental delays had the potential to slow this progress.

Knowledge of these factors can help to predict outcomes for individual implant candidates. However, the accuracy of such predictions remains limited and should be used only as a guide. Further investigation of the relationship between language abilities and speech perception in implanted children is needed to improve our understanding of their interaction. There is also a need for additional factors to be addressed, including pre-implant residual hearing, psychophysical parameters such as number of electrodes used and electrical dynamic ranges, and psychosocial issues that may influence outcomes for some implanted children. This study provides clear evidence of the potential of multichannel cochlear implants to provide useful speech perception for hearing-impaired children, and knowledge of individual factors that can give reasonable estimates of outcomes prior to implantation.

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