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MULTICHANNEL COCHLEAR IMPLANTATION IN CHILDREN: A SUMMARY OF CURRENT WORK AT THE UNIVERSITY OF MELBOURNE

Richard C. Dowell, M.Sc., Pam W. Dawson, M.A., Shani J. Dettman, B.Sc., Robert K. Shepherd, Ph.D., Lesley A. Whitford, Dip Aud., Peter M. Seligman, Ph.D.,* and Graeme M. Clark, Ph.D.*

ABSTRACT

This paper summarizes research work relating to multichannel cochlear implantation in children at the University of Melbourne. Ongoing safety studies relating to the implantation of young children are discussed. Results of these studies suggest that special design considerations are necessary for a prosthesis to be implanted in children under the age of 2 years. Results of clinical assessment of implanted children and adolescents are also discussed in terms of speech perception, speech production, and language development, and some possible predictive factors are suggested. Preliminary data suggests that a high proportion of young children can achieve open-set speech perception with the cochlear implant given appropriate training and support. Initial results with adults using new speech processing hardware and a new coding scheme are also presented. These suggest that improved speech perception in quiet and competing noise is possible with the new system.

The Department of Otolaryngology at the University of Melbourne has been involved with cochlear implant research for almost 20 years. During the early and mid-1970s, initial physiologic and safety studies established the feasibility of a multichannel cochlear prosthesis to assist profoundly deaf people.[1] The improvement in electronics technology during this time made possible the development of a prototype 10-channel prosthesis that was implanted in three volunteer subjects in the late 1970s.[2]

Psychophysical studies with these subjects led to the first successful speech processing scheme that presented amplitude, voice pitch, and second formant information (F0F2), and encouraging speech perception results were soon obtained.[3] This work, between 1979 and 1981, provided invaluable experience and knowledge for the design of the commercial implant and speech processor in 1981 and 1982. Commercial development, made possible by an Australian Federal Government grant to Nucleus Ltd., allowed the University and Nucleus to work closely together, providing a balance of research and manufacturing expertise that led to the development of a safe, reliable, 22-channel prosthesis, which underwent clinical trials in 1982 and 1983.

Initial results showed that profoundly, postlinguistically deafened adults obtained significant improvements in speech perception with and without speechreading.[4] Further studies indicated that many subjects using the multichannel prosthesis could understand a significant amount of unknown, connected speech without speechreading.[5] Independent studies have indicated that, in general, this level of speech perception is available only to subjects using multichannel cochlear implants.[6] Continuing psychophysical studies led to the development of a more advanced speech processing scheme that added first formant information to the existing scheme (F0F1F2) in 1985. This provided improved speech perception for implanted subjects, particularly for open-set, auditory-alone material.[7] With the development of a miniaturized version of the 22-channel device incorporating an implanted magnet, the prosthesis was suitable for implantation in children.

This paper discusses the main results obtained with children implanted in Melbourne over the last 4 years in terms of speech perception, production, and language development. Basic research aimed at investigating some of the important long-term safety issues regarding implants in children are discussed as well as new developments in speech processing that have important implications for the future application of the prosthesis.

SAFETY STUDIES

Temporal Bone Growth

This study is aimed at determining the changes over time in the distance between the anatomic sites that could

Department of Otolaryngology, University of Melbourne, East Melbourne, Australia
*Cochlear Pty Ltd, Lane Cove, NSW, Australia
Reprint requests: Richard Dowell, Department of Otolaryngology, 2nd Floor, 32 Gisborne St., East Melbourne, 3002, Victoria, Australia

be used to fix the electrode, lead wire, and implant package in young children. To this stage, results have shown that there are certain fixation points (e.g., the fossa incudis) where the distance from the round window remains fixed from birth to death. Figure 1 shows the distance between the round window and the fossa incudis as measured on a series of temporal bones from children aged 0 to 11 years. These results indicate that this distance remains fixed from birth at approximately 9 mm. Other points, with age, show increasing distance from the round window. For example, Figure 2 shows the distance from the round window to the mastoid tip as measured on a series of temporal bones from children aged 0 to 11 years. These results suggest that this distance increases from approximately 12 mm at birth to approximately 24 mm by age 6 years. A fixed point, such as the fossa incudis, therefore provides a preferable fixation point for the electrode lead wire in young children. Studies have confirmed that the distance from the round window to the implant-package bed does change significantly with age up to 2 years. This means that, for children under 2 years, a special expanding lead-wire assembly may be required.

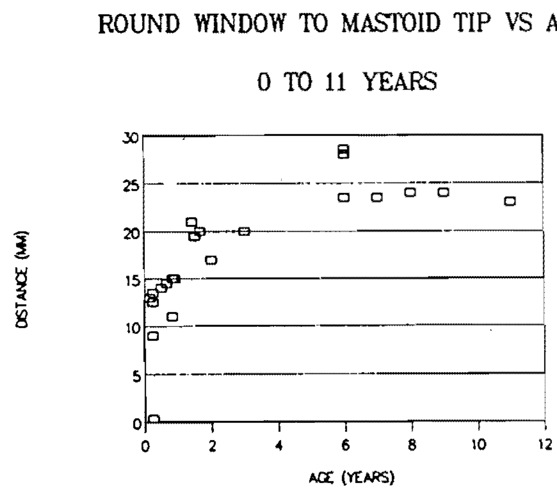

Figure 2. Distance from the mastoid tip to the round window as a function of age as measured from a series of human temporal bones.

Method of Fixation

This study aims to determine a means of fixing the electrode, lead-wire assembly and implant package so that temporal bone growth will not result in the electrode being withdrawn from the cochlea, electrode-wire fracture, or displacement of the implant package. A technique has been developed for fixing the electrode to the floor of the antrum using a teflon-coated platinum wire as a tie.[8] The efficacy of this fixation technique is being assessed in monkeys.

Lead-Wire Lengthening

As the anatomic studies have shown that the distance between the round window and the implant package bed may increase by 10 to 15 mm over time, there is a need to ensure that the lead wire can expand without traction being applied to the electrode or the implant. A number of expandable lead-wire designs have been assessed by implanting 3-month-old kittens. Initial results have shown that a helical coil arrangement is unsatisfactory as fibrous tissue ingrowth impairs its expansion (Fig. 3). It appears that a U-shaped redundancy enclosed in a thin Silastic bag provides the best system for the required expansion.

Effects on Skull Growth

It was considered to be important to assess carefully the possible effects on skull growth of cochlear implant surgery in young children. This has been investigated by implanting young Macaque monkeys and monitoring subsequent skull growth radiologically. Figure 4 shows results of these studies to date. The difference between the lateral skull width on the implanted and nonimplanted side is plotted here as a function of age in months for five monkeys. This difference does not exceed 1 mm for any of the monkeys at any stage

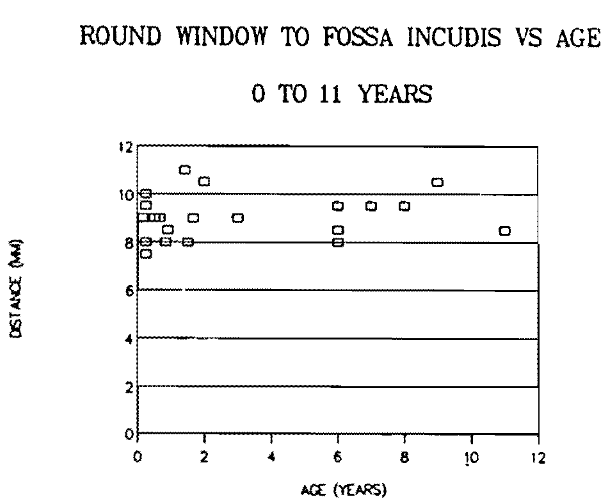

Figure 1. Distance from the fossa incudis to the round window as a function of age as measured from a series of human temporal bones.

Figure 3. Helical coil being excised from a young cat as part of the lead-wire lengthening studies. Note the fibrous tissue impeding the expansion of the coil.

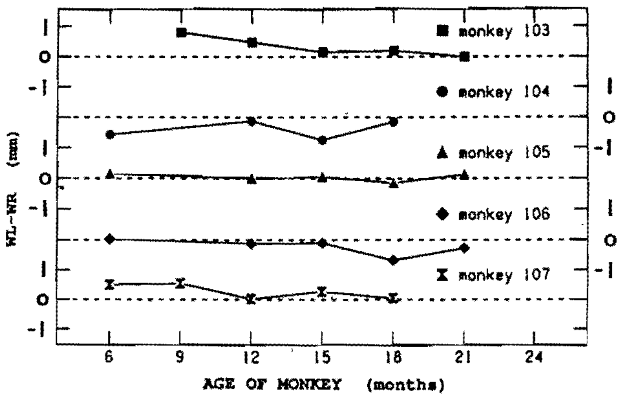

Figure 4. Symmetry of skull growth in implanted monkeys measured as the difference between the lateral skull width on the implanted and nonimplanted side.

and no significant difference is evident between the implanted and nonimplanted side in this series. At this stage, these results indicate that the effect of implantation on skull growth should not be a concern when implanting young children.

Effect of Middle Ear Infection

For some time there has been concern that, in young children who are prone to otitis media, the placement of an intracochlear electrode will increase the risk of labyrinthitis or meningitis. Studies to assess various methods of sealing the round window have been carried out by implanting experimental animals and inoculating the middle ear with bacteria. The use of a teflon felt collar glued to the electrode did not provide a better result than using no material at all, while the use of Dacron produced a strong foreign body reaction that tended to aggravate infection around the electrode.[9] It has been found that the fibrous tissue sheath that forms around the electrode provides an effective barrier to the spread of infection.[10] It is important to remember, however, that this sheath takes 2 to 3 weeks to form and infection that is present at the time of surgery or occurring soon after implantation is more likely to spread to the cochlea.[11]

Safe Electrical Stimulation Parameters

Studies have already demonstrated that the electrical stimulus parameters used in the multichannel cochlear implant have no adverse effects on the cochlea or auditory neurons. Nonetheless, further studies are being undertaken to confirm that they are safe for young children. Deaf kittens are being implanted and stimulated for 8 hours per day for 1,200 to 1,600 hours. Electrically evoked brainstem responses have shown little change during long-term stimulation indicating no adverse effect on spiral ganglion cells. Figure 5 shows the amplitude of the electrically evoked auditory brainstem response as a function of stimulating current before chronic electrical stimulation and after 200, 400, 600, and 800 hours of stimulation for an implanted cat. The amplitude function shows no significant change at any stage. Damage to ganglion cells in the cochlea due to the chronic electrical stimulation would be expected to cause a flattening of the amplitude growth function of the brainstem response.

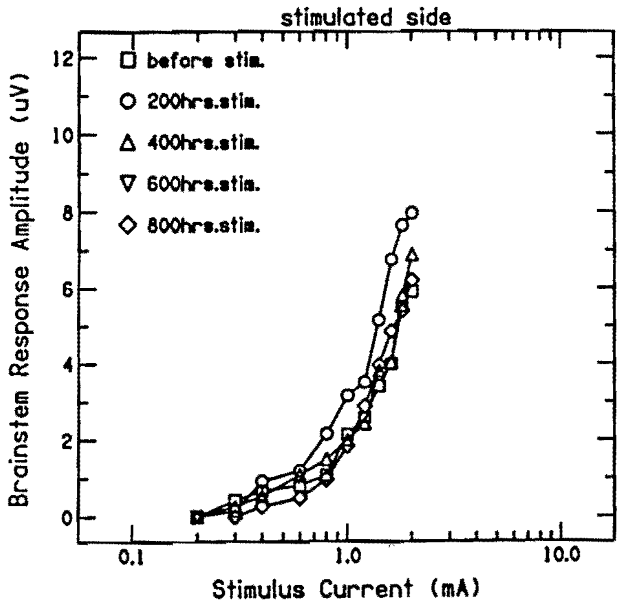

Figure 5. Amplitude growth function of the auditory brainstem response in an implanted cat after various periods of chronic electrical stimulation of the auditory nerve.

Extracochlear Stimulation

Although there are now improved methods of measuring hearing loss in children under 2 years of age, there is still a risk that an intracochlear electrode may damage undetected residual hearing in this age group. Extracochlear electrical stimulation may be a feasible alternative in these young children; therefore, studies are being undertaken to determine the effect of extracochlear stimulation on residual hair cells and spiral ganglion cells. Additional studies will attempt to determine whether true multichannel stimulation is possible with extracochlear electrodes.

MELBOURNE CLINICAL PROGRAM

The children's implant program at the University of Melbourne and the Royal Victorian Eye and Ear Hospital has developed over a period of 4 years. Throughout this time there has been a strong emphasis on incorporating the cochlear implant into all aspects of the implanted child's life. This has required a commitment to long-term support for each child and special attention to providing information to parents, teachers, and other professionals involved with the child's management. Each child has been provided with training from our implant clinic staff for at least 6 months prior to implantation and for up to 3 years following surgery. Parents and teachers are encouraged to take part in training sessions with the aim of providing consistent habilitation outside these sessions. We have found the 6-month preoperative period to be very important, particularly for young children. This allows parents an adequate time to come to terms with the responsibilities and implications of cochlear implantation for their child. It also allows an adequate review of the child's residual hearing, aided potential, and speech and language development. Since 1988, the training program for young children has developed into a predominantly auditory-verbal approach. There has been a general improvement in speech perception results since this approach has been adopted, and although it is difficult to separate the effect of experience, the results suggest that the new approach has been more efficient in developing auditory skills.

SPEECH PERCEPTION RESULTS

A total of 21 children and adolescents have been implanted in Melbourne. These children can be loosely divided into three main categories.

(1) Postlinguistically deafened children: These children have had enough hearing to develop adequate speech and language through audition and have been implanted shortly after becoming profoundly deaf. Results for this group have been equivalent to postlinguistically deaf implanted adults and they have demonstrated open-set speech perception ability soon after implantation. Only two adolescents implanted in Melbourne fall into this category.

(2) Congenitally or early-deafened young children: This group has shown the ability to develop open-set auditory-alone speech perception using the implant. A total of 12 children in this category have been implanted in Melbourne. Six of these are too young for formal testing, although informal assessment on imitative auditory tasks have been encouraging. Two of the children were implanted recently and data is not available as yet. The other four children have shown some open-set auditory-alone speech perception on standard formal tests. The time required to attain good speech perception performance has varied from 9 months to 3 years, that is, there has not been evidence of open-set speech perception in any of these children immediately after implantation.

(3) Congenitally or early-deafened adolescents and young adults: There are seven implanted subjects who fall into this category. At this stage, no subjects in this group have demonstrated open-set speech perception to any significant extent. However, improvement in speech perception with speechreading has been demonstrated and significant closed-set results have been obtained. All subjects in this group are full-time users of the prosthesis.

A total of five children (four congenitally or early-deafened young children and one postlinguistically deafened adolescent) with long-term data have demonstrated open-set speech perception and their results are shown in Figure 6. It is important to note that these results were obtained on standard tests designed independently to assess speech perception ability in the hearing-impaired population. The children did not have any training on the test material and only a single presentation was allowed.

Summaries of individual speech perception results for two young children and two teenagers are shown in Figure 7(*A–D*). These subjects have been chosen as representative of the two main categories previously referred to and are not the best performers in each age group. They have been implanted for more than 2 years, so these results represent relatively long-term performance with the implant. Child A

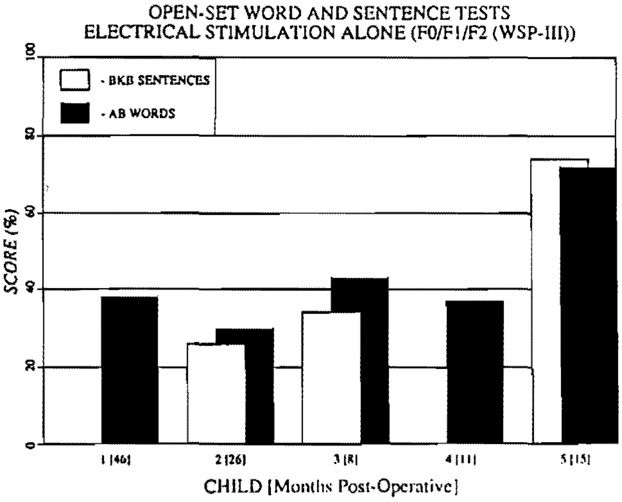

Figure 6. Open-set speech perception results for five children implanted with the multichannel cochlear prosthesis. The subjects are numbered as for Figures 8 and 9.

(subject 2 in Figs. 6, 8, and 9) became profoundly deaf at the age of 3 years following meningitis and had been deaf for 2 years, 6 months prior to implantation. His educational program was based on cued speech. Child B (subject 3 in Figs. 6, 8, and 9) had congenital profound deafness of unknown origin and was implanted at the age of 8 years. Her educational program was also based on cued speech. Child C had congenital total deafness due to Ushers syndrome with associated visual problems. Her educational program at the time of implantation involved cued speech although she had previous experience in a total communication setting. Child D had congenital total deafness due to the Mondini dysplasia and had been educated in a total communication setting.

Six scores are shown for each subject, the first four being subtests from the PLOTT test,[12] which assess specific speech feature discrimination. The scores have been adjusted such that 0 percent represents chance performance for these closed-set tests. It is evident that all four subjects perform well for vowel place, consonant manner, and consonant voicing discrimination. For the consonant place subtest, performance is relatively poor although one child scores well (child B). This is consistent with results for adults using the multichannel implant, which also indicate poor consonant place discrimination. The Northwestern University Children's Speech Perception (NUCHIPS)[13] test is a four alternative closed-set test that, in general, requires consonant discrimination to select the correct item. The scores presented here also have been adjusted such that 0 percent is equivalent to chance performance. All four subjects score significantly above the chance level and scores are consistent across the group. The closed-set results indicate that these four children with different ages, onsets, and causes of deafness appear to receive similar auditory information via the cochlear implant. The results are consistent with the large amount of data obtained on adult subjects for speech feature discrimination tasks. This is encouraging, as three of these children were congenitally deaf and implanted after the age of 7 years. However, there is an obvious difference between the two teenagers and the younger children when the open-set sentence results are reviewed. The younger children are scoring at a level con-

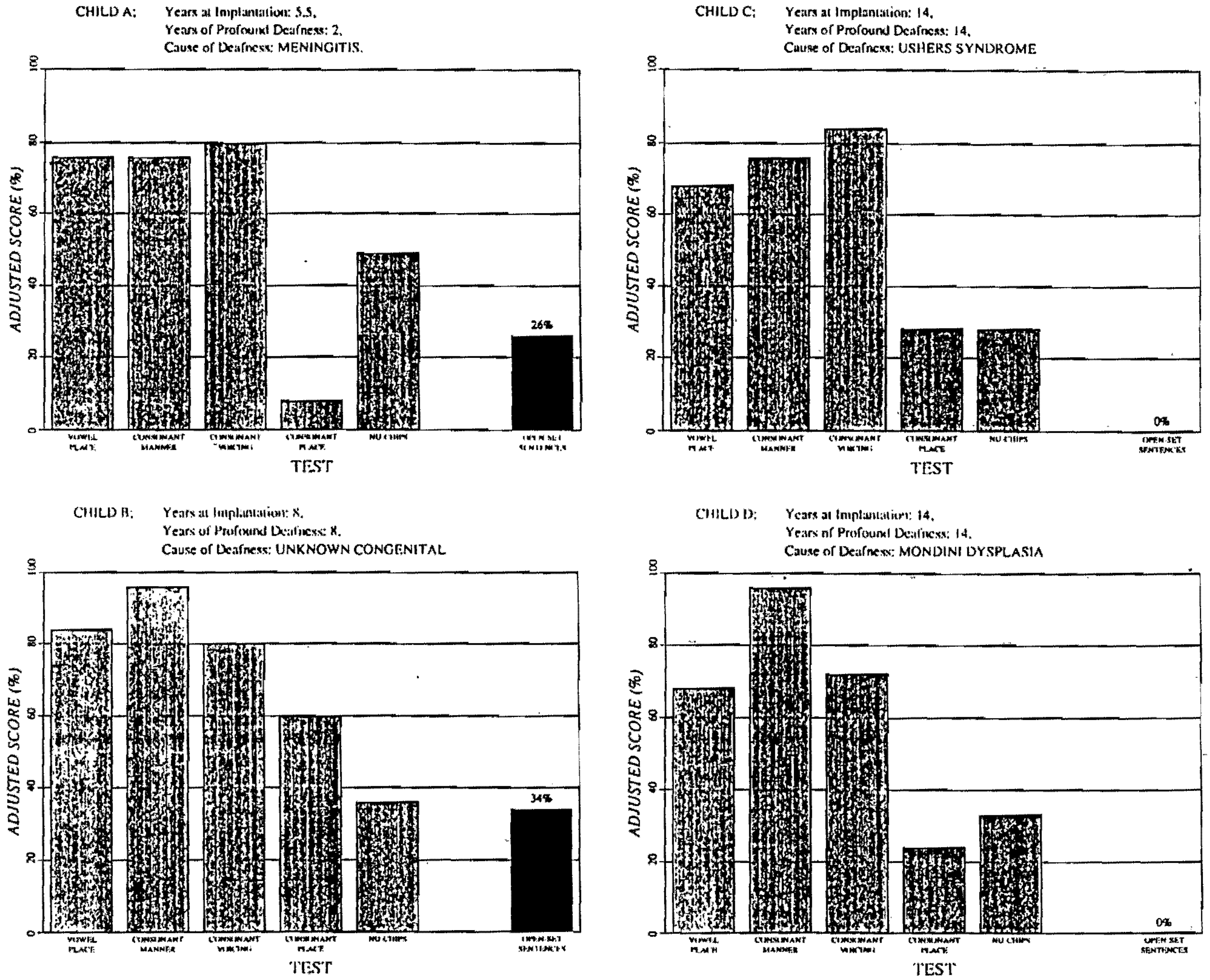

Figure 7(*A–D*). Individual speech perception results for four implanted children and adolescents. Scores for closed-set tests have been adjusted such that 0 percent represents chance performance. Also shown are the age of the child at implantation and the onset and cause of profound deafness. Note that child A and child B are also included in Figures 6, 8, and 9 as are subjects 2 and 3, respectively. Child C and child D are not included in Figures 6, 8, and 9.

sistent with the performance of postlinguistic adults (the mean postoperative score for postlinguistically deafened adults is 36 percent), whereas the adolescents received a score of 0 percent on this test. Many factors could contribute to this problem including: changes in neural plasticity with age; the fact that the adolescents tend to have a well-established visual language system; differences in home and school environments and the expectations of teachers, family, and friends. It is clear that the older subjects have great difficulty processing auditory input at the rate required to cope with connected speech. Despite the lack of open-set results for the teenagers, they show significant benefit for closed-set speech perception, communication with speechreading and recognition of environmental sounds.

SPEECH PRODUCTION

All children in the Melbourne program have had ongoing assessment of speech production and intelligibility at approximately 6-month intervals. Whenever possible, two assessments were obtained during the preoperative training period prior to implantation. This gives some scope for separating the effect of training and maturation from that of the implant. Figure 8 shows results over time for the four young children who have long-term data on articulation measures.[14,15] The numbering of subjects here is the same as for Figure 6, which showed open-set speech perception results. Significant improvements were evident for each child from the pre- to the postoperative period. It is interesting to note that there is an initial drop in scores immediately after implant surgery. This may be due to the trauma of the operation and the discontinuity in training while the device is being programmed appropriately.

LANGUAGE DEVELOPMENT

Long-term results from language assessments have shown encouraging improvements for the young implanted children. Again, it is difficult to separate training effects from device effects. Language results have been analyzed in terms of equivalent age in an attempt to compare changes

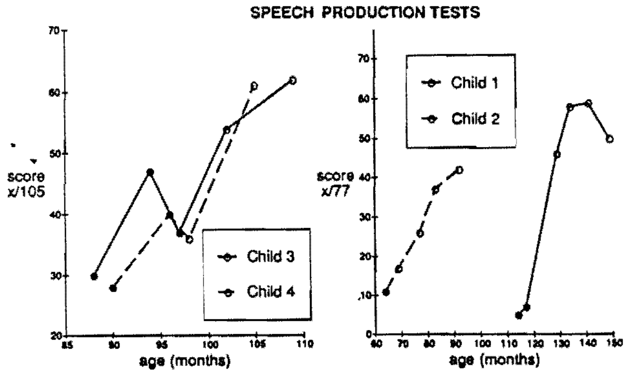

Figure 8. Results of articulation tests over time for four children implanted with the multichannel cochlear prosthesis. Filled circles represent preoperative data and open circles, postoperative data. Significant improvement is evident from pre- to postoperative for all four children. The subjects are numbered as for Figures 6 and 9.

with those expected due to maturation. Figure 9 shows results for the four young children with long-term data on the Peabody Picture Vocabulary Test,[16] with equivalent age, obtained from the test score, plotted against chronologic age. These are the same subjects whose open-set speech perception results are presented in Figure 6 and whose speech production results are presented in Figure 8. A regression analysis was carried out on these results and asterisks indicate significant improvement over time. The slope of the regression line (the b value) is greater than 1 in three of four cases, indicating that these children have improved on this task at a faster rate than expected for normally hearing children at the same language level.

NEW SPEECH PROCESSING DEVELOPMENTS

During the last few years, Cochlear Pty. Ltd., with the assistance of the University of Melbourne, has developed a new speech processor for the multichannel implant system. This new processor, known as the MSP, is smaller and lighter than the existing processor (WSP-III), and the electronics have been improved. A new speech coding scheme has also been introduced after preliminary studies showed encouraging results. The new scheme builds on the existing F0F1F2 processor that presented amplitude, voice pitch, and first- and second-formant information via the implant. The MULTIPEAK scheme presents these acoustic features and additional information from three high-frequency spectral bands.[17] The aim of the MULTIPEAK scheme was to provide additional consonant information and in this way give better performance in moderate levels of background noise.

Initial results with the new system have been encouraging and have indicated that both the new speech processing hardware and the MULTIPEAK coding scheme provide improved open-set performance in quiet and in competing noise. Figure 10 shows results for two matched groups of adult subjects, one group using the WSP-III speech processor and the other using the new MSP with the MULTIPEAK coding scheme. Scores for the BKB open-set sentence test[18] in quiet and with various levels of competing noise are significantly better for the MSP group. Figure 11 shows results for five individual subjects using the WSP-III speech processor, the MSP processor with the F0F1F2 coding scheme, and the MSP processor with the MULTIPEAK coding scheme. These subjects were assessed with BKB open-set sentences in quiet over four test sessions with each system. For each subject, significant improvement was evident with the new processor and the new speech coding scheme. These results support the matched group studies and both studies indicate a change in mean open-set sentence scores from approximately 50 percent with the WSP-III to 85 percent with the MSP using the MULTIPEAK coding scheme. It is hoped that this improvement will carry over to all implanted subjects, including children. A number of children have been switched over to the new system and have accepted it well, however, there are no comparison results available at this stage.

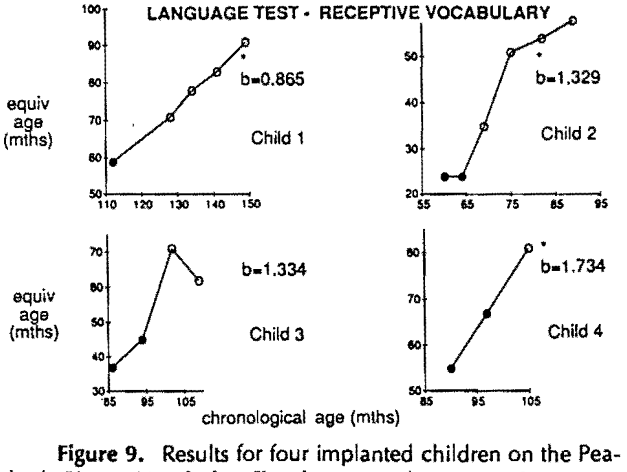

Figure 9. Results for four implanted children on the Peabody Picture Vocabulary Test for pre- and postoperative assessments. Scores are represented as equivalent age plotted against chronologic age. Filled circles represent preoperative data and open circles, postoperative data. The b values represent the slope of regression lines fitted to the data. The subjects are numbered as for Figures 6 and 8.

SUMMARY

Studies are continuing to assess the long-term safety of cochlear prostheses for young children. Results so far have suggested that special design considerations will be necessary for the implantation of children under the age of 2 years due to temporal bone growth. Various methods of electrode fixation and lead-wire expansion are being investigated. Other issues, such as the safety of chronic electrical stimulation of the maturing auditory nerve, and the consequences of middle ear infection for the implanted cochlea are also being studied. These studies should allow the design of a prosthesis and surgical procedure that will be safe in the long term for children under the age of 2 years.

Results for implanted children have shown improvements in speech perception, speech production, and language, and, in general, the best results have been seen in younger children (pre-adolescent). Significantly, open-set speech perception has been achieved for a high proportion of young children,[19] including some with congenital profound deafness. Results for congenitally deaf adolescents have not demonstrated open-set speech perception ability; however, with consistent support, these children have become successful users of the cochlear prosthesis.

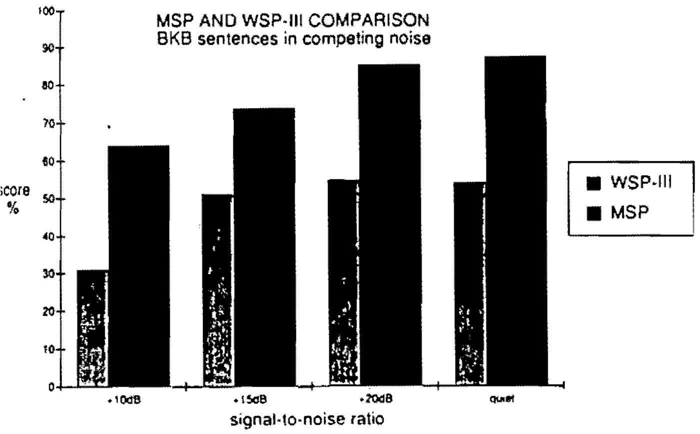

Figure 10. Open-set speech perception (BKB sentences) in quiet and in competing noise for two matched groups (n = 4) of adult subjects using the multichannel cochlear prosthesis. Group A (*darker bars*) used the WSP-III speech processor with the F0F1F2 coding scheme and group B (*lighter bars*) used the new MSP processor with the MULTIPEAK coding scheme. Scores were obtained over four test sessions for each subject.

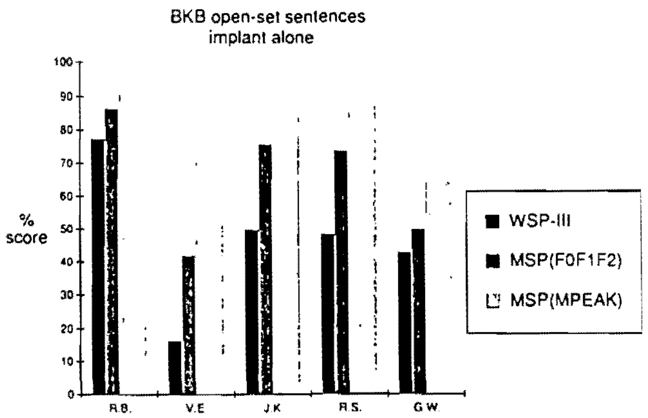

Figure 11. Open-set speech perception (BKB sentences) in quiet for five individual adult subjects using the WSP-III speech processor with the F0F1F2 coding scheme (*lighter bars*), the MSP processor with the F0F1F2 coding scheme (*gray bars*), and the MSP processor with the MULTIPEAK coding scheme (*darker bars*). Scores were obtained over four test sessions for each subject and condition.

Preliminary results for adult subjects using the new MSP speech processor have shown significant improvements in speech perception in quiet and in competing noise and it is hoped that the new device will provide better performance for implanted children.

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