In 1978-79, a speech processing strategy which extracted the voicing (F0) and second formant (F2) frequencies and presented these as rate and place of stimulation respectively to residual auditory nerve fibres was developed for the University of Melbourne's prototype multiple-channel receiver-stimulator (Clark et al 1977, Clark et al 1978, Tong et al 1980). This speech processing strategy was shown to provide postlinguistically deaf adults with some open-set speech comprehension using electrical stimulation alone, and considerable help when used in combination with lipreading (Clark et al 1981). In 1982, a more reliable multiple-channel cochlear implant was developed by Cochlear Pty. Limited, and implanted in a further group of postlinguistically deaf adults. The F0/F2 speech processing strategy was tested using the receiver-stimulator, and found to provide the same good results demonstrated on the first group of patients operated on at the Royal Victorian Eye and Ear Hospital (Pyman et al 1983). This multiple-channel implant and F0/F2 speech processor was then trialled on patients at centres in the U.S., and was approved by the U.S. Food and Drug Administration (F.D.A.) in October 1985.

The studies at the University of Melbourne showed that although the F0/F2 multiple-channel speech processor could provide patients with open-set speech recognition for electrical stimulation alone, the results were still below the ideal, particularly the perception of consonants. It was considered that more frequency spectral information, provided by extracting both the first formant (F1) as well as F2 and presenting these as place of stimulation, would improve the results. Initial psychophysical studies showed that a two-component sensation was produced (Tong et al 1983). An acoustic modelling experiment which simulated multiple-channel electrical stimulation on normal hearing subjects also showed that an F0/F1/F2 strategy should provide improvements in speech perception (Blamey et al 1984). These predictions were confirmed when implant patients used the F0/F1/F2 strategy (Dowell et al 1987). This was then incorporated into Cochlear's wearable speech processor and was referred to as WSPIII. This was approved by the F.D.A. for use on postlinguistically deaf adults in May 1986.

Furthermore, in 1983, having obtained good results with the F0/F2 speech processing strategy on postlinguistically deaf adults, the next decision was to determine if prelinguistically deaf adults could benefit. Two patients (Clark et al 1987b) aged 24 and 23 years, who communicated with signed English and sign language of the deaf, were operated on at the Royal Victorian Eye and Ear Hospital on 20 September 1983 and 15 November 1983 respectively. They were then studied over many months. It was found that their ability to perceive both place and rate pitch was poor, but they had good loudness discrimination (Busby et al 1986, Clark et al 1987a, Tong et al 1988). It was not possible to provide these two patients with a communication system that could be combined with their signing. As a result of this work it was concluded that multiple-channel implants on prelinguistically deaf adults probably would not be of significant benefit as the maturation of central processing for speech had occurred a number of years earlier. It was subsequently found, however, following an operation on 17 September 1985 on a 22 year old woman, born severely deaf and who had lost residual hearing over a few years, that she was able to get some open-set speech recognition. This was attributed to the fact that she had exposure to speech sounds while her auditory pathways were maturing (Clark et al 1987b).

Having concluded that it was desirable to implant prelinguistically and postlinguistically deaf children rather than prelinguistically deaf adults, an implant operation was carried out on a 14 year old boy who had been deaf from meningitis at 16 months. The operation was undertaken at the Royal Victorian Eye and Ear Hospital on 8 January 1985. Psychophysical studies indicated that he had some place and rate pitch perception, but not at a level that was normal for postlinguistically deaf adults. His speech perception was helped a little when the device was used in conjunction with lipreading, but he had no open-set speech recognition for electrical stimulation alone (Clark et al
1987a, b, Tong et al 1988). Subsequently, we learned that this patient was able to improve his speech perception and production with specific training, but still did not get open-set speech recognition with electrical stimulation alone (Busby et al in press). The results, although only from one patient, suggested that even teenagers may not get a great deal of benefit and that it would be necessary to operate on younger children. This presented a problem as the teenager, and all other patients at the time, received the Cochlear Pty Limited multiple-channel receiver-stimulator which was 11 mm thick and had to be used in conjunction with a speech processor transmitter coil that was worn on a head band.

It was appreciated that if younger children were to be implanted, a smaller device would need to be made as our measurements of skull thickness at the implant site showed that the bone was too thin to accommodate the 6 mm ‘stalk’ section of the ‘mushroom-shaped’ 11 mm thick implant. It was considered that a total thickness of 6 mm rather than 11 mm was necessary to prevent the device protruding too far either internal or external to the cranium. This could be achieved if the connector section of the Cochlear Pty Limited device was removed. The connector had been included to allow the package to be replaced, leaving the electrode in situ if the electronics or package subsequently failed. Experimental animal research and human surgical experience at the University of Melbourne had shown, however, that the smooth, tapered, banded, free-fitting electrode could be removed easily and another one inserted without difficulty (Clark et al 1987c).

It was concluded that a new receiver-stimulator could be designed without the connector, and therefore made smaller. Furthermore, the problem of a child having to fit a head band and keep it in place, while playing, was overcome by using rare earth magnets in the centre of the implanted receiver and externally worn transmitting coils. Rare earth magnets had been previously incorporated in the 3M House single channel device as advocated by Dormer et al (1980). The receiver-stimulator that had the above improvements was named the mini-22 device by Cochlear Pty Limited, and is still the current model.

Prior to implanting further children it was realized that their evaluation and training would be more involved than for postlinguistically deaf adults. There would be a need to determine whether the implant helped them, not only with speech perception, but speech production, receptive and expressive language, and communication skills. Their habilitation or rehabilitation could also take longer and require more intensive training.

In 1985 at the University of Melbourne, a team approach to the management of children was developed and this team included otologists, audiologists, speech pathologists and educators of the deaf (Busby et al 1987). In addition, a training and assessment program was created (Nienhuys et al 1987).

When the assessment and training program was in place, the mini-22 receiver-stimulator was implanted in the first child. This was a 10 year old boy who became profoundly deaf following meningitis at 3.5 years. The operation was at the Royal Victorian Eye and Ear Hospital on 20 August 1985. The device performed to specifications and preliminary results showed that he was able to obtain help in understanding speech when combined with lipreading compared with lipreading alone, but no open-set speech recognition with electrical stimulation alone (Clark et al 1987a, b, Busby et al 1989). In view of the difficulty in again obtaining open-set speech with electrical stimulation alone with this child, a decision was made to implant a younger child. This was a 5 year old boy who had also lost hearing from meningitis at age 3 years. The operation was performed on 15 April 1986. In his case, the preliminary results were much more encouraging and it was not long before he began to obtain some open-set speech recognition with electrical stimulation alone (Clark et al 1987a, b, Dawson et al 1989, in press). The initial results obtained with the above child then encouraged the University of Melbourne group to proceed with multiple-channel implants and include younger children as well as those who were congenitally deaf.

The F.D.A. approved its evaluation on 75 adolescents and 75 children from two years of age and above. At the start of the F.D.A. clinical trial on children, a conference was organized in Durango, Colorado, 20-22 February, 1986. This was an A.S.H.A. approved continuing education program (Mecklenburg et al 1986). At this conference it was stressed that the pre- and post-operative evaluation should be directed towards the assessment of phonetically significant details of the speech signal, and not on the auditory thresholds as they only had relevance in a child with some hearing. It was also emphasized that tests of expressive and receptive language were as important as those of speech perception and production. Psychosocial issues such as family support were also important.

At the time of the Premarket Approval (P.M.A.) submission there was 12 months data on 80 children in the above two groups, but 200 had been implanted overall. Data from clinics in Melbourne as well as Sydney were included in the F.D.A. trial (The University of Sydney, Cochlear Implant Team operated on their first child—a 16.8 year old post-meningitic adolescent on 11 June, 1986).

In Melbourne, while carrying out our research on children it was found that nearly half were able to obtain some open-set speech recognition with electrical stimulation alone (Dawson et al 1989, in press). We learned, however, that an auditory/oral training approach was needed and the therapists were required to be fully supportive. This also became the experience with the U.S. centres. The centres that had a team approach with good habilitation and rehabilitation care obtained the best results.

It is now useful to assess all the children that have been studied in the U.S. and Australia with a battery of age appropriate speech perception tests.

The study has been undertaken on 142 children who have been using the Cochlear mini 22-electrode cochlear implant for periods of time ranging from eighteen months to four years (Staller et al 1991). The results in this joint study were obtained from 23 centres in the United States and Australia. They include data from 80 children who were part of a clinical evaluation by Cochlear Corporation for the U.S. Food and Drug Administration. The average age of the children at surgery was 9.2 years; the range was 2.1 to 16.9 years. The proportion of prelinguistically deaf children (children who went deaf at less than two years of age) was 66%. Furthermore, 44% of the children were congenitally deaf. In the study, there were approximately equal numbers of males and females, and 54% of the children had been
trained using total communication before surgery, that is, they used some signed English as well as auditory/oral information. The cause of the deafness in the implanted children was largely meningitis or unknown, and this accounted for 84% of the pathologies.

The implant and receiver-stimulator used for children was the same as the one for adults. The surgery was also similar to that for adults. Any differences in technique were due to the smaller size of the child's skull. A more detailed account of the surgery for children two years of age and older, and the difference in technique from that in adults, is discussed by Clark et al (1991). Surgery was not carried out on children under two years of age as there are a number of additional safety factors in this group, such as head growth and middle ear infections, which need to be resolved (Clark et al 1991).

The speech processor used for the children was mainly the WSP/III (FO/FI/F2) version. This WSP/III processor has subsequently been superseded by the MSP-MULTI PEAK Speech Processor, and the results for the new device are significantly better than for the WSP/III processor when evaluated in adults (Dowell et al 1990, Skinner et al 1991). As the results in this paper are predominantly for children using the WSP/III processor it would be expected that children may perform better when they are changed over to the MSP device.

When assessing the speech perception performances of the children in this study, it was considered important to use tests that were appropriate for each particular child's language development. It is also important to remember that a deaf child's language is not as well developed as that of a normal hearing child. Furthermore, different categories of speech perception were assessed using separate tests. The categories of tests used varied in their level of difficulty and were for: sound detection; speech patterns; closed-set word recognition; and open-set word and sentence recognition. The tests were also carried out using hearing or electrical stimulation alone, and some tests were used to determine how electrical stimulation helped with lipreading.

The results of tests used to show how well the children could recognize speech patterns are shown in Figure 1. The tests were the monosyllable/trochee/spondee MTS stress test, male/female discrimination, and the spondee same/different test. The average results shown in Figure 1 are better for postoperative electrical stimulation compared to preoperative acoustic stimulation for all the tests. The individual results, however, vary and there are some children who do not show any significant improvement. The results for 60 children tested with the MTS stress test are shown in Figure 2. 15 (25%) could perform above the 95% confidence level preoperatively and 49 (82%) postoperatively.

The results of tests for closed-set word recognition are shown in Figure 3. The tests were the MTS word, CID spondee and monosyllable identification, four choice spondees, and the NU-CHIPS test. These tests vary in the age or language level required to perform them and some use pictures as alternatives so they can be used by deaf children with poor speech. With every test there was a significant improvement for electrical stimulation postoperatively compared to residual hearing preoperatively. The individual results for the MTS word test for the 60 children using electrical stimulation alone are shown in Figure 4. 13% were above the 95% confidence levels preoperatively and 62% postoperatively. Notice also that the postoperative scores were well above the preoperative scores in most children.
Preoperative 95% Confidence  
- 12 Months Postoperative 
Chance

**FIG. 4.** Individual pre and postoperative MTS word identification scores for 60 children.

**FIG. 5.** Pre and postoperative open-set speech identification scores.

The performance category varied from only being able to detect sound to the identification of open-sets of words and sentences. The performance categories, in order of difficulty, were detection of sound, recognition of speech patterns, closed-set word identification and open-set word and sentence identification. The results for postlinguistically deaf children are shown in Figure 7. Preoperatively, most of the children were in the detection of sound or recognition of speech pattern categories. Postoperatively, many more children reached the closed and open-set word identification categories. They, of course, could also recognize speech patterns and detect sound.

The results above were for postlinguistically deaf children, but what of the prelinguistically deaf children who are born deaf or become deaf before two years of age? Their results have been analyzed separately and are shown in Figure 8. This figure shows the maximum performance categories reached by the prelinguistically deaf children preoperatively and postoperatively. As with the postlinguistic results in Figure 7 many more children reach the closed-set and open-set categories postoperatively. The proportion of prelinguistically deaf children doing this is similar to the proportion of postlinguistically deaf children. This suggests that both pre and postlinguistically deaf children obtain significant benefits from a cochlear implant.

Although each child did not receive every test, each child did at least receive one test in each category or group of tests. As a result, it is possible to classify each child according to the highest performance category reached both preoperatively and postoperatively. Their maximum performance category varied from only being able to detect sound to the identification of open-sets of words and sentences. The performance categories, in order of difficulty, were detection of sound, recognition of speech patterns, closed-set word identification and open-set word and sentence identification. The results for postlinguistically deaf children are shown in Figure 7. Preoperatively, most of the children were in the detection of sound or recognition of speech pattern categories. Postoperatively, many more children reached the closed and open-set word identification categories. They, of course, could also recognize speech patterns and detect sound.

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LIPREADING ENHANCEMENT

Lipreading Alone vs Lipreading with Electrical Stimulation

![Graph showing lipreading enhancement with electrical stimulation for open-sets of CID sentences and closed-sets of WIPI words.]

FIG. 9. Lipreading enhancement with electrical stimulation for open-sets of CID sentences and closed-sets of WIPI words.

The results discussed so far have been for electrical stimulation alone. The children were also tested to see how electrical stimulation could assist with lipreading. The average results in all children tested for lipreading alone and lipreading plus electrical stimulation for open-sets of CID sentences and closed-sets of WIPI words are shown in Figure 9. These show significant improvements when lipreading is combined with electrical stimulation compared to lipreading alone.

The results presented have all been recorded 12 months postoperatively. In the case of adults, the scores improve over time and this is seen with the children in this study.

As shown (Figures 10, 11), the improvement over time applies to all categories of tests and there is evidence that the children's performance is continuing to improve even after 36 months.

The results have been analyzed to see what factors correlate with good speech perception performance. The children with no open-set perception have been compared with those getting open-set speech recognition. There were nearly equal numbers in each group. The results showed that children do better if they become deaf when they are older, have used the device for a longer period of time, and a greater number of electrodes have been used.

It is important to emphasize that this work has been a team effort. Without a team consisting of otologists, audiologists, speech pathologists, educators of the hearing impaired and social workers, the results for children would not be as good as they might otherwise have been.

Finally, the Department of Otolaryngology at the University of Melbourne has a U.S. National Institutes of Health Contract ‘Studies on Pediatric Auditory Prosthesis Implants’ in which studies are being undertaken to examine safety issues for multiple-channel cochlear implants in children under two years of age. If operating on children of this age has no harmful effect there would be benefits in exposing them to speech sound presented through the implant in the same way that it is better to fit a hearing aid to a deaf child under two.

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