The time course of F2 is depicted in the right-hand panel of Fig. 2, the values of F2 produced by the same speakers are represented preimplantation and I year postimplantation in comparison with the norm values of van Nierop et al. For 6 of the 8 male speakers there is a trend for F2 to reach the target positions. A tendency to change in the direction of the target positions is also observed with the 12 female speakers.

For the distances along the F2 dimension a significant effect of implantation was observed (F[2,38] = 3.6, p < .05). In all subjects in the upper four panels in Fig 2, together with the norm values represented by the curves and the standard deviations of the norm values. The results of the 8 male speakers and the 12 female speakers are depicted separately. Figure 2 clearly shows that more vowels fall within their normal range 1 year after implantation.

The deviation of F1 from the norm values for the individual vowels preimplantation and postimplantation is displayed for all subjects in the upper four panels in Fig 2, together with the norm values represented by the curves and the standard deviations of the norm values. The results of the 8 male speakers and the 12 female speakers are depicted separately. Figure 2 clearly shows that more vowels fall within their normal range 1 year after implantation.

For the distances along the F2 dimension a significant effect of implantation was observed (F[2,38] = 3.6, p < .05). The time course of F2 is depicted in the right-hand panel of Fig 1. The mean values of the F2 distances to the norm values are 229.7, 211.2, and 197.1 Hz, respectively. Subsequent Scheffé tests demonstrated a significant decrease of the F1 distance 3 months postimplantation (p < .01) and 12 months postimplantation (p < .001) versus preimplantation. The left-hand panel of Fig 1 displays the distances to the norm values along the F1 dimension for the preimplantation and the postimplantation conditions. The mean values of the F1 distances to the norm values are 105.4, 86.6, and 78.7 Hz, respectively. For the majority of subjects the vowels take more appropriate positions along the dimension of the first formant postimplantation. Of interest, in 3 subjects the F1 distance increased at 3 months postimplantation, to show improvement after only 12 months of implant use.

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Physiological and phonological changes in the connected speech of children using a cochlear implant

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INTRODUCTION

In excess of 5,000 children, with profound hearing impair-
This topic is of interest because the speech of young prelingually or postlingually deaf children is in a constant state of development. The effectiveness of the implant, therefore, must be measured in its ability to provide enough auditory information for the child to develop intelligible speech. This is in addition to the maintenance of intelligible speech in the case of older postlingually deaf children or adults. The aim of the present study was to investigate some characteristics of the connected speech of a selected group of children from the University of Melbourne Cochlear Implant Programme. More specifically, the study aimed to determine how these characteristics changed over time. Studies of conversational speech samples are useful in that they do not depend on imitation yet they do reflect the child’s everyday communication skills and are sensitive to co-articulatory effects. Analyses performed on the preoperative and postoperative data aimed to detect both the phonetic and phonologic changes in the segmental features of speech. The following questions were addressed: 1) What was the pattern of change in the phonetic inventories from before to after implantation? 2) Was there a difference in the correct production of consonants depending on their position in the word? 3) Did the group performance for correct production of phonemes change significantly from before to after implantation? 4) Did performance change over time for individuals? 5) What were the most common phonologic processes and was there a significant reduction in any of these processes from before to after implantation?

**METHOD**

Twenty children from the Melbourne Cochlear Implant Programme were selected for this study. The subjects were divided into two groups of 10 depending on their level of intelligible speech preoperatively. Intelligible speech was defined as being recognizable to the speech pathologists who analyzed all samples. Group 1 subjects had speech that was mostly babble or unintelligible preimplant. Group 2 subjects had mostly intelligible speech preimplantation. Postoperatively, all subjects had speech that was mostly intelligible. Group 1 subjects’ ages ranged from 1 year 6 months (1y6m)
to 5y1m (mean, 3y4m) preoperatively and 3y5m to 8y2m
(mean, 6y) postoperatively. The average length of use of
implant was 2y6m. Five of the children were in an auditory­
oral educational setting and 5 in total communication. The age
range for the children in group 2 was 3y4m to 8y10m (mean,
6y3m) preoperatively and 5y1m to 11y10m (mean, 8y8m)
postoperatively. Average length of implant use was 2y2m.
Seven of the children were in an auditory­oral setting and 3
were in total communication.

Two samples were chosen for each child on the basis that
the preoperative sample was as close to the date of implant as
possible and the other was as recent as possible. All samples
featured the child on videotape interacting with a familiar adult.
Props such as toys, family photographs, books, and pictures were
used to facilitate a conversational speech sample of
at least 6 minutes (mean, 13 minutes). A minimum of 50
utterances was transcribed for all samples, with the exception
of 8 group 1 samples and 4 group 2 samples because the sample
was less than 50 utterances. A computer program, written
as part of a larger research project entitled Computer Aided
Speech and Language Analysis (CASALA), was used to col­
late and statistically analyze the data. Phonetic inventories
were plotted from the broad transcriptions from group 1 sam­
ples. A phoneme was considered present in the child’s reperto­
ire if it occurred at least once. The samples from group 2
were transcribed narrowly and the percentages of correctly
produced phonemes for vowels, consonants, and clusters (ini­
tial, medial, and final positions) were compared. The relative
occurrence of phonologic processes was also computed and
investigated for this group.

RESULTS

The phonetic inventories for group 1 indicated that for
vowels (Fig 1A), all monophthongs were represented pre­
implant, with the low-central vowels and schwa being present
in the inventories of 8 or more children. Postimplant, all
vowels, including diphthongs, increased in representation.
High and mid-front vowels and some of the high and low­
back monophthongs were now present in the inventory of 8 or
more children. Diphthongs were still relatively underrep­
resented. In Fig 1B, consonants were arranged in the order of
acquisition for normal-hearing children.7 Preoperatively, 40%
or more of the subjects used [w, m, b], [d], and [j] for place
characteristics and [b, d], [m], [h], and [w, j] for manner.
Voiceless phonemes were infrequently used. Postoperatively,
only [ch, v, th, zh] were used by less than 40% of the children.

An analysis of variance on the group 2 data indicated that
initial consonants were the most accurately produced, fol­
lowed by medial and final, which were the least accurate (p <
.001). The average total percentage of correctly produced
vowels, consonants, and clusters indicated a significant im­
provement from before to after implantation (p < .001; Fig
2A). The χ² analyses of the preimplant and postimplant sin­
gle-subject data for the number of correctly versus incorrectly
produced phonemes showed that 80% of the subjects im­
proved significantly on production of vowels, 60% on conso­
ants. Consonant deletion was the only process that was
significantly reduced from before to after implantation (p <
.05 Wilcoxon signed-rank test).

DISCUSSION

The change in the phonetic inventories from before to after
implantation indicated that over time, the acquisition of
sounds became closer to that of normal-hearing children.
Other researchers have studied phonetic changes in implanted
groups of subjects. There are similarities in the general pattern
of results, although direct comparison is difficult because of
the wide range of methodologies and analyses used. In the
present study, for vowels, monophthongs were used more
frequently both before and after implantation with an increase
in the use of diphthongs postimplant. Geers and Tobey,3
investigating vowel accuracy, reported that diphthongs were
generally less accurate than monophthongs. The results from the present study indicated that the most commonly used monophthongs preimplant were mid-front, mid-central, and low-central. Postimplant, 70% or more of the subjects used all the monophthongs. Osberger et al. also found a higher percentage of central and middle vowels in their preoperative sample, with an increase in the high-front vowels postimplantation. In other words, the inventory became more like that of normal-hearing children, who initially use front vowels more than central or back, and high more than middle or low.

For consonants, preimplant, 40% or more of the subjects used one or two members of the stop, nasal, glide, and fricative categories. The most common place characteristics was bilabial, and for manner and voice characteristics, voiced stops were predominant. These results are supported by those found in other studies,4-6 although none reported the frequent use of the fricative [h] found in the present study. Researchers have concluded that more visible consonants were easier for subjects to produce than the less visible, and that the acquisition of fricatives, liquids, glides, voiceless consonants, and high-front vowels were the most difficult for hearing-impaired children. The preimplant results reported here would support these notions. There was an increase in almost all the consonants postimplant. For place characteristics, alveolars had the greatest relative increase in representation, followed by velars, labiodentals, interdentals, bilabials, and palatals, respectively. For manner characteristics, the greatest increases were in liquids, followed by stops, fricatives, nasals, affricates, and glides, respectively. The frequency of voiceless cognates increased more relative to voiced and particularly voiceless fricatives. In summary, use of liquids, alveolars, and glides was more likely to increase with time, followed closely by stops and velar consonants. Other studies have reported similar findings, although some have reported a higher production of stops and nasals relative to other features postimplant, despite increases in fricatives, liquids, and glides. It is clear that the spread of results in the postimplant inventory in Fig. 1B more closely resembles the pattern of consonant acquisition of children with normal hearing (i.e., decreasing from top to bottom) than the preimplant inventory.

A significant difference was found for the correct production of consonants, depending on their position in the word. Initial consonants were found to be more accurately produced than medial, and final consonants were the least accurately produced. This is an important finding, as other studies on phoneme accuracy did not differentiate between initial, medial, and final positions. The reason for the apparent difficulty in accurately producing final consonants is an area for further study. Murphy and Dodd reported that a high number of deletions of final consonants is common in the speech of hearing-impaired children, as opposed to initial and medial, and this may, at least in part, be the reason for significantly more final consonant errors.

The group performance for correct production of vowels, consonants, and clusters did significantly improve from before to after implantation. Other studies on phoneme accuracy in implanted subjects confirm this result. Individual results in the present study provide further information on differences among the three groups of phonemes. Eighty percent improved significantly on vowel accuracy and 60% on consonants. Thirty percent of the subjects improved on vowels and consonants, and a further 30% on vowels, consonants, and clusters. No subjects improved on consonants or clusters alone. This suggests that vowels are easier to produce than consonants. Clusters are clearly the most difficult for implanted subjects to produce accurately.

The most common phonologic processes occurring both preimplant and postimplant for vowels were elongation, nasalization, and monophthongization. Deletion, voicing, stopping, and cluster reduction were most common for consonants. The reduction in consonant deletion postimplantation was the only process to reach statistical significance for the group, despite the fact that several other processes were reduced considerably for individual subjects. Possibly because of the relatively small number of subjects, consonant deletion had the most opportunity to occur, whereas other processes affect only a small number of targets. The above list of processes was compared to one described by Murphy and Dodd in relation to hearing-impaired speakers with similar results. A more narrow classification system such as final and initial consonant deletion, prevocalic voicing, and postvocalic devoicing was used by Murphy and Dodd, and these may be useful in future studies in order to study more closely the patterns of phonologic changes over time.

The results from this study suggest that as a group, children receiving a multichannel cochlear implant improve on their segmental features of speech production in everyday conversation over time. Younger children acquired more phonemes with time and used speech that had a greater proportion of recognizable words. Certain vowels and consonants were more likely to be acquired, depending on the place and manner of articulation. Older children's production of phonemes became more accurate with time. Gains are most likely due to a combination of maturation, habilitation, and implant experience.

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