Special lecture

MULTICENTER EVALUATIONS OF SPEECH PERCEPTION IN ADULTS AND CHILDREN WITH THE NUCLEUS (COCHLEAR) 22-CHANNEL COCHLEAR IMPLANT

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Introduction

The Nucleus 22-channel cochlear implant has been implanted in over 10,500 patients in 79 countries, and used for more than 25 languages. It arose as a result of our early physiological, behavioral and biological research on experimental animals[1-5]. The historical development of the Nucleus device has been outlined in detail by Clark[6]. Our ongoing research has led to improvements in the way speech is processed with the 22-channel device that are now resulting in improved speech perception for profoundly totally deaf people that is, on average, better than the speech perception obtained by many deaf people with hearing aids. The multiple-channel cochlear implant was first approved by the US Food and Drug Administration (FDA) for use in postlinguistically deaf adults in 1985. It was subsequently approved for use in children in 1990. The proportion of children (18 years of age and under) to have now received it is approximately 43% (4,500 out of 10,500). In evaluating improvements in speech processing it is important to design well-controlled studies, and a number of important ones which have previously been published are summarized in this paper. In addition, speech perception results for all the Nucleus speech processing strategies have been obtained four to six months postoperatively from unselected patients presenting to the Cochlear Implant Clinic at the Royal Victorian Eye & Ear Hospital (RVEEH), Melbourne, and are presented in this paper. As results can vary greatly with different durations of experience it is essential to make comparisons at the same time postoperatively. These clinical data are the most complete to date for comparing the Nucleus speech processing strategies.

Inaugural speech processing strategy (F0/F2)–WSP II Speech Processor

Rationale

The present Nucleus (Cochlear) speech processing strategy SPEAK used with the speech processor SPECTRA 22 has resulted from research at the University of Melbourne that also led initially to the development of the inaugural F0/F2 strategy[7]. With the inaugural strategy developed in 1978 the second formant (F2) frequency was extracted and presented as place of stimulation, the fundamental or voicing frequency (F0) as rate of stimulation on individual electrodes, and the amplitude of F2 and later the speech wave envelope as the current level. Prior to developing the F0/F2 strategy we evaluated a fixed filter strategy which modeled the physiology of the cochlea

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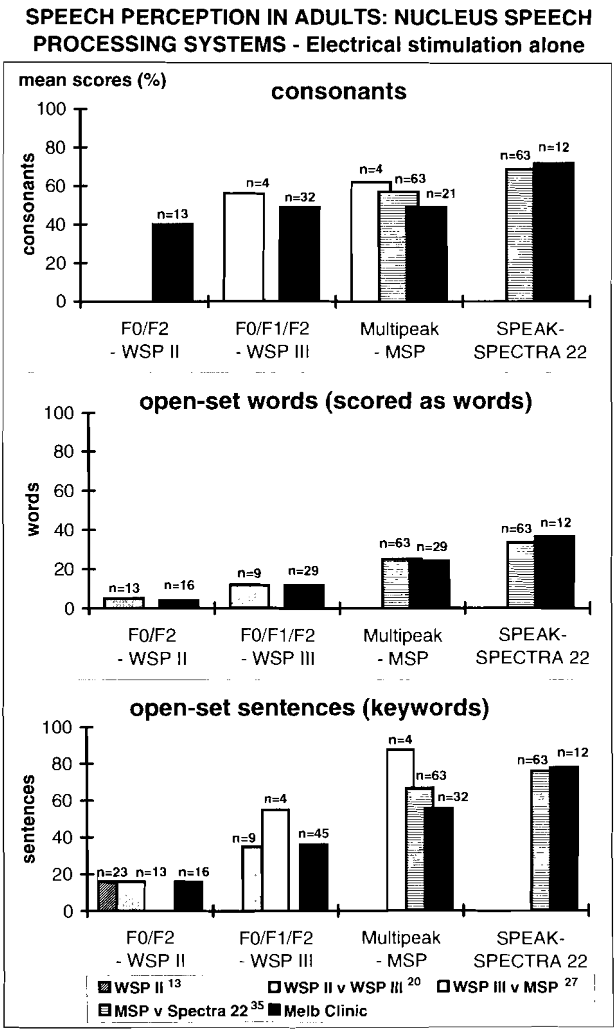

Fig. 1. Consonant, and open-set word and sentence scores for improvements in the Nucleus speech processing systems.

and the neural coding of sound[8]. With this fixed filter strategy unsatisfactory results were obtained due to simultaneous stimulation of electrodes (channel interaction). This difficulty was avoided with the inaugural F0/F2 strategy because only one electrode was activated at a time.

Results in postlinguistically deaf adults

Evaluation of F0/F2 University of Melbourne laboratory-based prototype speech processor

The inaugural F0/F2 strategy was first evaluated on two patients using a laboratory-based speech processor. The CID sentence test showed that the patients obtained marked improvements in communication (188% and 386%) when using electrical stimulation in combination with lipreading compared to lipreading alone[9]. For electrical stimulation alone, the average score for a closed-set of six vowels was 77%[10,11] and for a set of 12 consonants 34%[11]. The average score for tion using prerecorded test materials[12]. Similarly, scores on CID sentences (scored as key words) were 35% for live-voice and 11% when prerecorded[9].

Clinical trial of F0/F2–WSP II at nine centers worldwide

After it was established that the F0/F2 strategy used with the prototype speech processor enabled patients to obtain open-set speech recognition, the strategy was then implemented in the WSP II speech processor by Nucleus Limited. It was initially trialed for the FDA on 40 postlinguistically deaf adults from nine centers worldwide. Three months post-implantation the patients had obtained a mean CID sentence score of 87% (range 45-100%) for lipreading plus electrical stimulation, compared to a score of 52% (range 15-85%) for lipreading alone[13]. It was also found in a subgroup of 23 patients that the mean CID sentence scores for electrical stimulation alone rose from 16% (range 0-58%) at three months post-implantation (Fig. 1) to 40% (range 0-86%) at 12 months[13]. The F0/F2–WSP II was approved by the FDA in October 1985 for use in postlinguistically deaf adults.

Evaluation of F0/F2–WSP II at the University of Melbourne

The results for closed-sets of 12 consonants on 13 unselected patients at the RVEEH was 40% (Fig. 1). The results for open-sets of monosyllabic words on 16 patients were 4% when scored as words and 23% as phonemes. The CID sentences test result was 16% on 16 patients (Fig. 1).

Results in children

The F0/F2–WSP II system was first evaluated in children in Melbourne when a 14-year-old child (PS) had an implant on 8 January 1985, and commenced using the device on 19 March 1985. It was then assessed on a ten-year-old (SS) when the Nucleus (Cochlear) mini-receiver-stimulator, which was smaller and had a magnet incorporated, was implanted in SS on 20 August 1985. He commenced rehabilitation on 2 September 1985. The initial results showed increased scores for closed-set consonants and open-set words and sentences when electrical stimulation was combined with lipreading compared to lipreading alone. For electrical stimulation alone the scores for closed-sets of 12 consonants in the first child were 7% (a chance score), and for six consonants in the second child 31%[14,15].

F0/F1/F2 speech processing strategy–WSP III Speech Processor

Rationale

Our further research aimed, in particular, at improving the performance of multiple-channel speech processing for electrical stimulation alone both in quiet, and in the presence of background noise. Having presented the second formant or spectral energy in the mid-frequency region on a place coding basis, and found results for electrical stimulation to be consistent with those for single formant acoustic stimulation, the next appropriate task was to present additional spectral energy on a place coding basis. This possibility was supported by our psychophysical study[16] which showed that stimuli presented to two electrodes could be perceived as a two component sensation. To overcome the problems of channel interaction, first demonstrated in our physiological speech processing strategy in 1978, we used non-simultaneous, sequential pulsatile stimulation to stimulate two different sites within the cochlea for the F0/F1/F2 strategy.

The additional speech information to be coded on a place basis could have been energy in either the first or third formant regions. Providing first formant information was supported by the acoustic model studies on normally hearing individuals[17-19] which showed improved speech perception scores associated with the F1 information transmitted.

Results in postlinguistically deaf adults

Comparison of F0/F1/F2 with F0/F2 in quiet: University of Melbourne

The F0/F1/F2 speech processing strategy was implemented on the same speech processor as the F0/F2 strategy but now called WSP III, and first evaluated on patients in Melbourne in 1984. A comparison was then made in Melbourne of the F0/F2–WSPII and the F0/F1/F2–WSP III systems. The results for the F0/F2 strategy were obtained from 13 postlinguistically deaf adults and the results for the F0/F1/F2 strategy from nine patients[20]. The results for electrical stimulation alone were recorded three months postoperatively. The results for consonant discrimination were from the minimum auditory capabilities (MAC) battery and as these were from closed-sets of only four syllables they are not referred to. However, for 32 unselected patients at the Melbourne clinic using F0/F1/F2 the 12 consonant test result was 49% (Fig. 1). The CID sentence scores (Fig. 1) were 16% (F0/F2) and 35 % (F0/F1/F2), the monosyllabic words (scored as words) 5% (F0/F2) and 12% (F0/F1/F2) (Fig. 1), and the monosyllabic words (scored as phonemes) 23% (F0/F2) and 33% (F0/F1/F2). The improvements were all statistically significant[20–22]. On the unselected RVEEH clinic patients, the F0/F1/F2 mean scores for open-sets of words (scored as words) on 29 patients was 12% and when scored as phonemes 34%. The mean score for open-sets of CID sentences on 45 patients was 36%. An information transmission analysis of consonant perception for a small group of Melbourne patients showed that voicing, nasality and amplitude envelope information were all increased with the F0/F1/F2 strategy compared to the F0/F2[23].

Comparison of F0/F1/F2 with F0/F2 in noise: University of Melbourne

A comparison was made of the two speech processing strategies in background noise on a comparable group of patients who used the F0/F2 (n=5) and F0/F1/F2 (n=5) speech processing strategies[20]. The results of a four-choice spondee test using multi-speaker babble showed the F0/F1/F2 was significantly better at a signal-to-noise ratio of 10 dB. This F0/F1/F2–WSP III speech processor was approved by the FDA in May 1986 for use in postlinguistically deaf adults.

Results in children

Evaluation of F0/F1/F2–WSP III at the University of Melbourne

The first child in Melbourne to have the F0/F1/F2–WSP III system and mini receiver-stimulator was BD who was five years of age and operated on 15 April 1986. When this child was obtaining useful speech perception results, the number of children implanted and evaluated in Melbourne was increased, and in 1989 it was reported[24] that five children (aged six to 14 years) out of a group of nine had substantial open-set speech recognition for monosyllabic words scored as phonemes (range 30% to 72%), and sentences scored as key words (range 26% to 74%). Four of the five children who achieved open-set scores were implanted before adolescence, and the fifth, who had a progressive loss, was implanted as an adolescent. The children who did not achieve open-set speech recognition were implanted during adolescence after a long duration of profound deafness. The children who obtained open-set speech understanding, in particular, also showed improvement in language. The results were published in more detail by Dawson *et al.*[25].

Clinical trial of F0/F1/F2–WSP III at 23 centers worldwide

When the F0/F1/F2–WSPIII system was approved by the FDA for use in adults in May 1986, a multicenter clinical trial on children commenced. The results were obtained from 142 children at 23 centers. Results[26] were obtained for at least one speech test in the following speech perceptual categories: suprasegmental, closed-set word identification and open-set word recognition. The tests used were appropriate for the developmental stage of the child, and were administered 12 months postoperatively. The results showed that 51% of the children had significant open-set performance with their cochlear prosthesis compared with 6% preoperatively. In addition, 68% of the children could perceive some spectral cues for speech perception with their cochlear prosthesis compared with 23% preoperatively. Performance also improved over time with significant increases in open-set and closed-set speech perception between one and three years postoperatively.

When the test results on 91 prelinguistically deaf children in the study were examined separately, it was found that improvements were comparable with the postlinguistic group in many areas, however, performance was poorer on the open-set measures for the prelinguistic group. The F0/F1/F2–WSP III system was approved, by the FDA, for use in children on 27 June, 1990.

Multipeak speech processing strategy – MSP speech processor

Rationale

As the F0/F1/F2 strategy had given improved results when additional spectral energy in the first formant range was coded on a place basis, it was assumed there would be a further improvement if spectral energy in the third formant or high frequency region was coded on a place coding basis as well. It was anticipated this would lead to better consonant perception particularly for those consonants requiring more high frequency information, and that this would in turn lead to better speech perception. Energy in the frequency bands 2.0-2.8 kHz; 2.8-4.0 kHz; and 4.0-6.0 kHz was extracted and the energy in the first two bands together with the first and second formants used to stimulate four electrodes sequentially in the case of voiced sounds. This was the strategy for voiced sounds, as formants are important in the perception of vowels and voiced consonants. For unvoiced speech sounds, the energy in the above frequency bands together with the second formant were used to stimulate the cochlea on a place coding basis. The first formant was not used as energy in this region is minimal with unvoiced sounds. The strategy initially had a voiced /voiceless distinction, but this was not used in the commercial version. The speech processing strategy described above was called Multipeak, and it was implemented on a speech processor called (miniature speech processor) MSP.

The MSP differed from the WSP III processor in a number of ways. These included a selective increase of the signal in the second formant range, a new peak picking algorithm for F0, 256 rather than 32 amplitude levels, and a continuously variable sensitivity control. The Multipeak–MSP was approved by the FDA for use in postlinguistically deaf adults in October, 1989.

Results in postlinguistically deaf adults

Comparison of the F0/F1/F2–WSP III and Multipeak–MSP systems: University of Melbourne

An initial study was undertaken to compare a group of four experienced subjects who used the WSP III speech processor with the F0/F1/F2 speech processing strategy, and four who used the newer MSP speech processor and Multipeak strategy. It was fully realized that improvements in speech processor engineering seen with MSP as outlined above could affect the results. It was, however, necessary to show whether the proposed new MSP speech processor and Multipeak strategy were better than the WSP III processor and F0/F1/F2 strategy which were commercially available at the time. The patients were not selected using any special criteria except their availability and their willingness to participate in research studies. The results[27] showed, in quiet, a statistically significant difference for vowels (mean 78% F0/F1/F2–WSP III and 88% Multipeak–MSP) but not for consonants (mean 56% F0/F1/F2–WSP III and 62% Multipeak–MSP) (Fig. 1). Note the consonant scores for F0/F1/F2–WSP III were different from those obtained from the unselected Melbourne Clinic patients. This was probably due to the small sample size and previous experience with the device. For open-set BKB sentences there was a large statistically significant difference (mean 55% F0/F1/F2–WSP III and 88% Multipeak–MSP) (Fig. 1). Again the results were higher than for the unselected group from the Melbourne clinic (Fig. 1). When the performances of these two devices were compared in the presence of background noise the Multipeak–MSP results were significantly better. This applied to four-choice spondees at signal-to-noise ratios of 10 dB, 5 dB and 0 dB, and BKB sentences at signal-to-noise ratios of 20 dB, 15 dB and 10 dB. The four-choice spondee test was easier and results could be obtained at lower signal-to-noise ratios. It was also apparent that the differences in results became greater with lower signal-to-noise ratios. Additional studies with small groups of subjects suggested that both the engineering improvements and the new Multipeak strategy contributed to the improved speech perception results.

Comparison of the F0/F1/F2–WSP III and Multipeak–MSP systems: University of Washington

A study was then undertaken on patients at the Department of Otolaryngology, Washington University School of Medicine. This was carried out on seven postlinguistically deaf adults who used the F0/F1/F2–WSP III, F0/F1/F2–MSP, and Multipeak–MSP systems. When the F0/F1/F2–WSP III and F0/F1/F2–MSP were compared, there were no significant differences in speech perception scores. Consequently, any improvements seen with Multipeak–MSP in this study appeared to be not due to engineering improvements *per se* but to the speech processing strategy itself. When F0/F1/F2–MSP and Multipeak–MSP systems were compared, the Multipeak strategy gave significantly higher scores for open-set speech tests in quiet and in noise. The results were similar to those obtained in the Melbourne study. The Multipeak–MSP system was approved by the FDA on 11 October, 1989 for use in postlinguistically deaf adults.

Results in children

Comparison of the F0/F1/F2–WSP III and Multipeak–MSP systems: University of Melbourne

Ten children with the F0/F1/F2–WSP III system were changed over to the Multipeak–MSP system in 1989. Apart from an initial decrement of response in one child, performance continued to improve in five children and was similar for the other children. As a controlled trial was not carried out, it was not clear whether the improvements were due to learning or the new strategy and processor. The Multipeak–MSP system was approved by the FDA for use in children on 27 June 1990 on the basis of the F0/F1/F2–WSP III approval for children and the Multipeak–MSP approval for adults.

Spectral maxima speech processing strategy-(SPEAK) – SPECTRA 22

Rationale

While the above comparison of the F0/F1/F2–WSP and Multipeak–MSP strategies and processors was being undertaken, research was being carried out to further improve speech processing under an NIH contract NO1-DC-9-2400 'Speech Processors for Auditory Prostheses'.

In early 1989 a comparison was made between F0/F1/F2–WSP III and a strategy which estimated spectral peaks and was implemented on our Digital Signal Processor (DSP56001). With this strategy the three highest spectral peaks from 16 band-pass filters were selected and presented non-simultaneously to three electrodes on a place coding basis. A voiced/unvoiced decision was made by the same system used with the MSP processor, and voicing was coded as rate of stimulation. When this filter-bank three peak-picking strategy was compared with F0/F1/F2–WSP III, it was found the information transmission for vowels was better for the filter bank scheme, but the speech results were poorer[28]. This result may have been due to the patient having been a regular user of F0/F1/F2–WSP III.

As initial results with a scheme which picked three peaks and coded them as place of stimulation were not encouraging, a decision was made to develop schemes which picked more peaks (four and six), and another scheme which selected the six maximal outputs of the 16 band-pass filters, and presented these at constant rates to electrodes on a place coding basis. The latter is called the spectral maxima sound processor (SMSP) and is referred to below.

In 1989[29] the F0/F1/F2–WSP III was compared with three filter-bank schemes on two research subjects. In one strategy the three largest spectral peaks were encoded as place of stimulation, and F0 as rate of stimulation with random stimulation for unvoiced speech. With a second strategy the four largest peaks were encoded as place of stimulation, and F0 coded as for the first filter-bank strategy. With a third strategy the four largest spectral peaks were encoded as place of stimulation and groups of four current pulses presented at a constant rate of 125 Hz. The information transmission for vowels and consonants was statistically significantly better for the filter-bank schemes compared to the F0/F1/F2–WSP III. With the consonants this applied to duration, nasality and place. These improvements did not carry over to the tracking of speech, and this could have been due to the short periods of use with the filter-bank schemes.

In 1990[30] a comparison was made between the Multipeak–MSP system and a filter-bank strategy which selected the four highest spectral peaks and coded these on a place basis. Electrical stimulation occurred at a constant rate of 166 Hz which was a higher rate than in the strategy examined earlier. This strategy was also implemented using the Motorola DSP56001 digital signal processor. The results for vowels were as follows: patient KM-MSP (80%), DSP (77%); patient BG-MSP (71%), DSP (91%). The results for consonants were as follows: patient KM-MSP (77%), DSP (81%); patient BG-MSP (54%), DSP (81%). The improved results obtained for the DSP processor extracting four spectral peaks and presenting the energy as constant rate of stimulation suggested that this type of strategy could lead to better speech results than the Multipeak–MSP when further developed. To improve the strategy further, a decision was required on whether to have a strategy which presented six spectral peaks or six spectral maxima. As preliminary investigations did not show that six peaks made a significant difference, it was decided to proceed with a strategy which extracted six spectral maxima instead.

In 1990 the spectral maxima sound processing (SMSP) scheme was tested on an initial patient and found to give substantial benefit. For this reason, in 1990 a pilot study was carried out on two other patients who used the F0/F1/F2–MSP system[31]. The patients alternated in the use of the F0/F1/F2–MSP and SMSP–DSP schemes. The consonant scores for the two patients with the F0/F1/F2–MSP system were 20% and 16%, and for the SMSP–DSP 43% and 39%. The open-set CNC word scores (scored as words) were 9% and 1% for the F0/F1/F2–MSP system, and 21% and 16% for SMSP–DSP. The open-set CID sentence scores (scored as key words) were 53% and 56% for the F0/F1/F2–MSP system and 80% and 88% for SMSP–DSP. The Multipeak–MSP was evaluated on one of these patients and the results for electrical stimulation alone were: consonants 32%, CNC words 3%, and CID sentences 41%.

Results on postlinguistically deaf adults

Comparison of Multipeak–MSP and SMSP–DSP systems: trial at Melbourne

Due to the good initial findings described above, a more formal investigation was undertaken to compare SMSP–DSP with Multipeak–MSP[32]. The study was undertaken on four patients who had used the Multipeak–MSP for periods of time from 12 weeks to 16 months. An A/B design was used. The mean scores for vowels were 76% Multipeak–MSP and 91% SMSP–DSP. The mean scores for consonants were 59% Multipeak–MSP and 75% SMSP–DSP. The mean scores for open-sets of CNC words (scored as words) were 40% Multipeak–MSP and 57% SMSP–DSP. The mean scores for open-sets of CID sentences (scored as key words) in quiet were 81% Multipeak–MSP and 92% SMSP. The mean scores for open-sets of CID sentences at a signal-to-noise ratio of 10 dB (multitalker babble) were 50% Multipeak–MSP and 79% SMSP–DSP.

Comparison of Multipeak–MSP and SPEAK–SPECTRA 22 systems: clinical trial at eight centers worldwide

The SMSP strategy evaluated on our DSP speech processor[33] was developed industrially by Cochlear Pty. Limited as the SPEAK strategy and implemented on the SPECTRA 22 processor. The SPECTRA 22 processor differed from the MSP in having a bank of 20 filters rather than five filters[34]. This enabled six spectral maxima to be selected from 20 filters rather than 16 as with the SMSP. A comparison of the Multipeak–MSP and SPEAK–SPECTRA 22[35] systems was undertaken as a field trial on 63 postlinguistically deaf adults at: the University of Melbourne, Cochlear Implant Clinic, Royal Victorian Eye and Ear Hospital; Royal Prince Alfred Hospital, Sydney; the Denver Ear Institute; the Department of Otolaryngology, Washington University School of Medicine; Michigan Ear Institute; Sunnybrook Health Science Center, University of Toronto; St. Paul's Hospital, Vancouver; and South of England Cochlear Implant Centre, Institute of Sound and Vibration, University of Southampton. The experimental study was carried out using a single subject A/B:A/B design. For the medial vowel test, 25% of subjects had higher scores for SPEAK and 2% for Multipeak. The mean score for vowels was 75% for SPEAK and 70% for Multipeak and was statistically significant at the 0.0001 level. For the medial consonant test, 56% of subjects had higher scores for SPEAK and 0% for Multipeak. The mean score for consonants was 69% for SPEAK and 57% for Multipeak (Fig. 1) and was statistically significant at the 0.0001 level. For the CNC word test, 32% of subjects had higher scores for SPEAK and 2% for Multipeak. The mean score for words was 34% for SPEAK and 25% for Multipeak (Fig. 1) and was statistically significant at the 0.0001 level. For the CUNY and SIT sentence test in quiet, 39% of subjects had higher scores for SPEAK and 3% for Multipeak. The mean score for words in sentences was 76% for SPEAK and 67% for Multipeak (Fig. 1) and was statistically significant at the 0.0001 level. For the 18 subjects who had the CUNY and SIT sentence test at a signal-to-noise ratio of 5 dB, 78% of subjects had higher scores for SPEAK and 0% for Multipeak. The mean score for words in sentences was 60% for SPEAK and 32% for Multipeak, and was statistically significant at the 0.0001 level. The SPEAK–SPECTRA 22 system had a significantly better performance than Multipeak–MSP on all speech tests when evaluated using a paired t test (as a parametric test) or the Wilcoxon signed rank test (non-parametric test). SPEAK–SPECTRA 22 was approved by the FDA for postlinguistically deaf adults on 30 March, 1994.

Results on children

Comparison of Multipeak–MSP and SPEAK–SPECTRA 22: trial at Melbourne and Sydney

Given the reports of good benefits shown for adult patients using the SPEAK speech processing strategy, a number of important questions concerning the ability of implanted children to upgrade to the SPEAK speech processing strategy were raised. Firstly, while adult implant users had a previous knowledge of speech, would children who had effectively 'learned to listen' through their cochlear implant using the Multipeak strategy be able to adapt to a 'new' signal, and would they in fact benefit from any increase in spectral and temporal information available from SPEAK. Furthermore, as children are often in poor signal-to-noise situations in integrated classrooms, it was of great interest whether children using the SPEAK processing strategy would show similar perceptual benefits in background noise as those shown for adult patients.

To answer these questions, speech perception results for a group of 12 profoundly hearing-impaired children using SPEAK were compared with the benefits for the same children using the Multipeak speech processing strategy. The children were selected as being able to achieve a score for CNC words using electrical stimulation alone. The 12 children were assessed over a 36-week period. First, four evaluations with Multipeak were completed over an eight to 12 week period, followed by a further eight evaluations with SPEAK at three weekly intervals (24 weeks). The children were then switched back to Multipeak for a further evaluation. Following this, children used SPEAK for an additional six-month period, at which time a further evaluation was conducted.

At each evaluation, the children were assessed with two open-set speech materials, SIT sentences and CNC words, in both quiet and in a +15 dB signal-to-noise ratio situation. The materials were chosen on the basis that they were acceptable materials for children of the age range included in the study, and that there were sufficient lists to allow a new list for each test condition over an extended test protocol. The children were tested in both quiet and in noise to fully evaluate benefits which might be available in the classroom situation, which is often noisy.

All 12 children, seven from the Melbourne Cochlear Implant Clinic and five from the Sydney

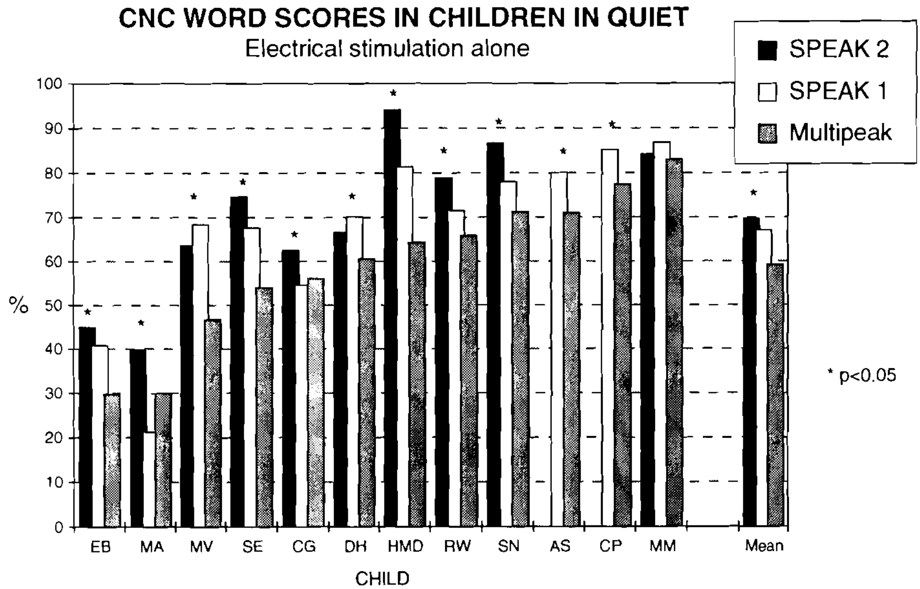

Fig 2. A comparison of 12 children of Multipeak and two SPEAK speech processing strategies using CNC word scores in quiet for electrical stimulation alone. SPEAK 1: initial evaluation at six months; SPEAK 2: second evaluation six months later.

Cochlear Implant Clinic, had over one year's experience with the Multipeak strategy. All the children were in the age range of six to 14 years, so that the vocabulary of the test materials, would be appropriate. The children also had open-set, implant-alone test scores on similar materials such as BKB sentences and PBK or AB words. It was decided to use only auditory alone open-set materials so that the influence of lipreading could be eliminated from the study. This increased the reliability of the hypothesis that any improvements shown would be due to the additional information provided by the SPEAK strategy.

Children were tested live-voice, and with recorded materials. For the live-voice testing, the same speaker was used for each child throughout the 36-week trial. Scoring was done by evaluating written responses from children where possible, or by independent scoring of the children's videotaped verbal responses by two clinicians.

Comparison of mean scores for the 12 children on open-set word and sentence scores showed a significant advantage ($p<0.05$) for the SPEAK strategy as compared with Multipeak in both quiet and in +15 dB signal-to-noise ratio. On SIT sentences, mean scores with SPEAK were 59.7% in quiet and 58.1% in background noise, compared with 52.7% and 48.3% using Multipeak. Similarly, mean scores on CNC words with SPEAK were 67.4% in quiet and 65.5% in noise, as compared with 59.4% and 57.3% with Multipeak. The SPEAK–SPECTRA 22 was approved by the FDA for children on 30 March, 1994.

Figure 2 shows individual scores for each of the children on open-set CNC monosyllabic words, scored by percentage phonemes correct, using electrical stimulation alone. For both Multipeak and SPEAK 1 (evaluation at six months), each bar represents an average score over four separate evaluations with each processing strategy. For SPEAK 2 (evaluation six months later than SPEAK 1), each bar represents an average score of two separate evaluations. As shown, individual scores varied across the children, however, children with both low and high open-set scores using Multipeak showed a significant increase when using SPEAK. In total, 11 of the 12 children showed significantly higher scores with SPEAK on at least one test material at the six-month evaluation (SPEAK 1). Following the initial six-month evaluation period, all 12 children opted to continue using the SPEAK processing strategy, including the one child (MA) who did not objectively show a benefit on the test materials. Subsequent to a further six months of experience, results for a repeat evaluation (SPEAK 2) with ten children are shown in Figure 2 (two of the children opted to withdraw from the study, although they have continued to use the SPEAK processing strategy). Results showed a further increase in mean scores with SPEAK to 69.9% on CNC words. Individual children again varied in improvements, however, child MA now shows a significant improvement with SPEAK compared to Multipeak.

Conclusions

With postlinguistically deaf adults, speech processing strategies which present additional spectral information have progressively improved word and sentence recognition, but have not had the same degree of improvement on consonants as shown in Figure 1, especially for the change from F0/F1/F2–WSP III to Multipeak–MSP. The mean score, however, increased from the Multipeak to SPEAK strategy, indicating a significant difference in the presentation of information. The results highlight the fact that improvements in speech perception are not necessarily proportional to changes in consonant test scores. The speech perception test results for SPEAK–SPECTRA 22 are now on average better than the speech perception obtained by many deaf people with hearing aids. With children, group comparisons have been more difficult, but as shown in Figure 2, improved scores can be obtained when more information is provided. At least 50% of prelinguistically and postlinguistically deaf children can obtain some open-set speech understanding using electrical stimulation alone. Furthermore, their central auditory processing can respond to the additional information provided with the SPEAK strategy.

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