Background: Previous research suggests that children with pure-tone averages of greater than 90 dB hearing level and/or open-set sentence perception of less than 30% may derive significant benefit from cochlear implantation.

Objective: To evaluate postoperative speech perception benefit and bilateral-bimodal benefit for 16 children whose preimplant speech perception scores exceeded conservative candidacy guidelines.

Study Design: Preimplant and postimplant repeated-measure design.

Methods: Sixteen child subjects who obtained 30% or greater on preimplant open-set sentence material, presented live voice audition alone, were selected for this study. Preimplant pure-tone averages ranged from 73 to 110 dB in the better aided ear. Preimplant and postimplant open-set word and sentence testing was completed in quiet and with competing background noise for separate ear and binaural conditions.

Results: Fourteen of 16 subjects had improved speech perception scores across all test materials after implantation. Group means were significantly higher for all test materials. Results in the bimodal-bilateral condition were significantly higher than implant alone for open-set word tests (scored for phonemes) and open-set sentences in quiet.

Conclusion: The results of this study suggest that, with appropriate counseling and management, some children with significant residual hearing benefit from cochlear implantation, in particular improved speech understanding due to bimodal-bilateral hearing.

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reported for obsolete speech processing hardware. These studies did not identify postoperative hearing aid use or report separate ear evaluations, and not all included speech perception evaluations under conditions of competing background noise.

It is important to examine a child's listening potential in everyday situations. Support for continued use of a hearing aid in the ear contralateral to the cochlear implant includes potential benefits of binaural hearing such as improved understanding in conditions of background noise and sound localization. Studies involving adults with acquired hearing loss have lent support for the continued use of a hearing aid in the ear contralateral to the cochlear implant because of potential benefits of binaural hearing such as improved understanding in conditions of background noise and sound localization skills. Only 3 studies to date have directly examined the use of the bimodal-bilateral device in the pediatric population. Chmeil and colleagues described enhanced speech perception and speech imitation skills in the bimodal-bilateral condition. Dettman and colleagues found significant improvements for bimodal-bilateral listening in noise compared with cochlear implant alone listening, when the noise source was on the same side as the implant. Ching and colleagues described improved speech perception in quiet and in conditions with competing background noise for most of their pediatric subjects. For children who did not demonstrate a binaural advantage they also showed no deterioration in performance with bimodal-bilateral stimulation compared with the cochlear implant alone.

Consideration of the cochlear implant for children with residual hearing has increased as recent studies have demonstrated that children who demonstrate preimplant open-set understanding also benefit from the cochlear implant because of potential benefits of binaural hearing such as improved understanding in conditions of background noise and sound localization. Only 3 studies to date have directly examined the use of the bimodal-bilateral device in the pediatric population. Chmeil and colleagues described enhanced speech perception and speech imitation skills in the bimodal-bilateral condition. Dettman and colleagues found significant improvements for bimodal-bilateral listening in noise compared with cochlear implant alone listening, when the noise source was on the same side as the implant. Ching and colleagues described improved speech perception in quiet and in conditions with competing background noise for most of their pediatric subjects. For children who did not demonstrate a binaural advantage they also showed no deterioration in performance with bimodal-bilateral stimulation compared with the cochlear implant alone.

There is a lack of research regarding outcomes of cochlear implants for children who obtain greater than 30% in preimplant open-set sentence understanding. Eisenberg and colleagues also suggested that preimplant testing should include separate ear testing, recorded materials, and the introduction of competing noise. The present study hypothesizes that postimplant open-set speech understanding for children with significant residual hearing will exceed preimplant performance. It is also hypothesized that this group of children will combine bilateral-bimodal signals effectively to aid speech perception.

METHODS

SUBJECTS

Sixteen children were selected who obtained greater than 30% correct open-set sentence understanding for live voice, audition-alone presentation. All children underwent routine medical, audiological, communication, and radiological assessment. Counseling with parents and children (where age appropriate) included information regarding equivalent hearing data, the importance of binaural hearing, and bilateral-bimodal research. The resultant informed decision to proceed with the cochlear implant was made by parents after discussion with clinicians, teachers, and surgeons. All 16 subjects were implanted with the Cochlear CI 24 multichannel implant and used either SPEAK or ACE speech processing strategy (Cochlear Ltd, Sydney, Australia). There were 15 children who had prelingual onset of profound deafness and one with perilinguistic onset at age 4 years. There were 9 children for whom a progressive course of hearing loss was noted. The mean onset of profound loss was 1.30 years and mean age at implant was 10.34 years. Demographic details for the individual subjects are presented in the Table and show a significant length of duration of profound hearing loss (mean, 9.03 years).

The 3-frequency PTA for the implanted ear ranged from 97 to 125 dB HL with a mean±SD of 109±9 dB HL. The 3-frequency PTA for the nonimplant ear ranged from 73 to 122 dB HL with a mean±SD of 96±11 dB HL. Using guidelines from Ching and colleagues, hearing thresholds exceeding the maximum level of the audiometer were assigned the value of the audiometer limit plus 5 dB to calculate the PTA. Fifteen of 16 subjects had a difference between their two ears in aided and unaided PTA. To minimize the risk of reduced auditory capabilities, the ear with poorer PTA and corresponding poorer speech perception scores was chosen for implant in 13 of 16 cases. For 1 child the PTA was identical (98 dB HL) in both ears. Two children received implants in the better PTA ear because they obtained consistently better speech perception scores using the poorer PTA ear. Before receiving the implant, all families and children were counseled that the child would be expected to wear the hearing aid in the nonimplant ear during the postimplant period.

SPEECH PERCEPTION TESTING

Before commencement of the study, children's speech processors and hearing aids were reviewed and volume settings were checked. An aided audiogram was obtained and the current speech processor program (“map”) was checked. The children used hearing aids with gain and other characteristics set according to the NAL-RP (National Acoustic Laboratories—Revised for Profound Hearing Loss) prescriptive formula. Hearing aids were not specifically modified or optimized for this study.

CONDITIONS

Most of the subjects were tested between 1 and 6 months before implantation. For those with fluctuating hearing loss, testing continued over a period ranging from 6 months to 4 years before implantation because these subjects were considered “borderline” candidates. The protocol for testing included separate ear and binaural testing for all test materials. Owing to clinical constraints and child factors such as fatigue and motivation, not all lists were completed for all children. In all cases the “best” representative preimplant data have been included for analysis. For those with progressive deterioration the “best” score once the child’s poorer ear dropped into the “profound range” was used for analysis. Postimplant data included the most recent “best” speech perception score, which, in most cases, was the bimodal-bilateral score. The duration of implant experience was 1.14 years (range, 0.51–2.14 years).

For ease of presentation, including all figures, the term binural hearing is used to refer to preimplant bilateral fitting of
hearing aids. In the postimplant period the use of the term binaural refers to the bilateral-bimodal fitting of hearing aid and cochlear implant/speech processor. There were 8 children who completed preimplant and postimplant separate ear and binaural testing using open-set word test materials. There were 9 children who completed preimplant and postimplant separate ear and binaural testing using open-set sentence materials with live voice presentation.

MATERIALS

Speech perception ability was assessed using open-set and closed-set word and sentence tests. One of 2 tests of open-set word identification was used. The Phonetically Balanced Kindergarten test is suitable for children with hearing loss who are 6 years and older. Words are presented in live voice, in isolation, and the child is prompted to imitate. There are 4 lists of 50 words and approximately 150 phonemes. Scoring takes into account the number of phonemes imitated correctly and the total number of correct words. The Consonant-Nucleus-Consonant test is another phonetically balanced test used to assess open-set word and sentence tests. One of 2 tests of open-set word identification was used. The Phonetically Balanced Kindergarten test was presented at 70 dB SPL from a CD player via speaker placed 1 m directly in front of the child. In the third condition, Bamford-Kowal-Bench sentences were presented at 70 dB SPL from the speaker in front of the child with coincident multiltalker babble at 60 dB A (thus, a +10-dB signal-to-noise ratio).

Both open-set word and sentence test procedures were video recorded within a quiet clinical environment, scored by 2 independent experienced listeners, and expressed as a percentage correct. In some instances of poor speech intelligibility the child would write his or her responses.

STATISTICS

Comparison of the best preoperative and best postoperative speech perception scores were performed using the Wilcoxon signed rank nonparametric statistical test as speech perception test scores did not follow a normal distribution. Data for separate ear and binaural speech perception scores were also analyzed in this way.

RESULTS

OPEN-SET WORD SCORES

Individual test results for 16 subjects for open-set word testing scored for phonemes correct (OSWph) are presented in Figure 1A and scored for total words correct (OSWw) in Figure 1B. The improvement on mean postimplant OSWph and OSWw was significant (OSWph mean difference = 23.6%, P < .001; OSWw mean difference = 30.6%, P < .001). There were 15 of the 16 subjects whose postimplant scores exceeded preimplant scores. Subject 1, whose postimplant scores (OSWph = 70%, OSWw = 32%) were poorer than preimplant scores (OSWph = 77%, OSWw = 51%), had a preimplant PTA in front of the child, for the binaural condition. The second condition included Bamford-Kowal-Bench lists presented with no competing noise at 70 dB SPL from a CD player via speaker placed 1 m directly in front of the child. In the third condition, Bamford-Kowal-Bench sentences were presented at 70 dB SPL from the speaker in front of the child with coincident multiltalker babble at 60 dB A (thus, a +10-dB signal-to-noise ratio).

Both open-set word and sentence test procedures were video recorded within a quiet clinical environment, scored by 2 independent experienced listeners, and expressed as a percentage correct. In some instances of poor speech intelligibility the child would write his or her responses.

Table 1: Demographic Data for 16 Children With Significant Residual Hearing

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Age at CI, y</th>
<th>Etiology</th>
<th>Onset of Profound Loss, y</th>
<th>Progressive</th>
<th>Age Aided, y</th>
<th>Duration of Profound Loss, y</th>
<th>Unaided CI Side PTA, dB HL</th>
<th>Oral/Sign</th>
<th>Unaided Hearing Aid Side PTA, dB HL</th>
<th>Best Preimplant BKB (Live)</th>
<th>Device*</th>
<th>Coding Strategy</th>
<th>Duration of Implant Use, y</th>
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<td>Genetic</td>
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<td>30</td>
<td>Sprint SPEAK</td>
<td>2.14</td>
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</table>

Mean: 10.34 1.30 1.44 9.03 109 96 54 1.14

Abbreviations: BKB, Bamford-Kowal-Bench sentence test; CI, cochlear implantation; CMV, cytomegalovirus; EVA, enlarged vestibular aqueduct; HL, hearing level; PTA, pure-tone average.

*All devices are manufactured by Cochlear Ltd, Sydney, Australia.
the better ear of 73 dB HL and had only 6 months’ device experience.

OPEN-SET SENTENCE UNDERSTANDING

Live Voice Presentation

Individual test results for 16 subjects for open-set sentence testing with live voice presentation (OSS-Live) are presented in Figure 2A. The OSS-Live mean improvement from 53.8% preimplantation to 87.3% postimplantation was significant ($P < .001$). For 15 of 16 subjects the postimplant scores exceeded preimplant scores for OSS-Live understanding. Only for subject 1 was the postimplant score (78%) poorer than the preimplant score (87%).

Recorded Presentation in Quiet

All 16 subjects were tested postoperatively with recorded open-set sentence lists in quiet (OSS-Q) (Figure 2B) with a mean score of 85.38%. The group mean OSS-Q improvement from preimplant score to postimplant score was significant ($P < .005$). Thirteen subjects were tested before implantation with a mean score of 36.01%. For 12 of these subjects individual postimplant performance exceeded preimplant scores. Best preimplant score of 52% for subject 7 was with binaural hearing aid fitting, whereas the only postimplant score available for comparison was using the cochlear implant alone (44%).

There were 3 subjects (subjects 8, 15, and 16) who were not tested before implantation with OSS-Q. (Their preimplant OSS-Live scores were 30%, 34%, and 30%, respectively.) Postimplant OSS-Q performance exceeded preimplant OSS-Live performance for all 3 cases, with scores of 92%, 92%, and 78% for subjects 8, 15, and 16, respectively.

Recorded Presentation With +10-dB Signal-to-Noise Ratio

There were 14 subjects who were tested postoperatively using recorded open-set sentences with +10 dB competing multitalker babble (OSS+10) (Figure 2C) with a mean score of 61.71%. Seven subjects were tested preoperatively in this condition with a mean score of 28%. Postimplant scores exceeded preimplant scores for all 7 subjects who completed testing. The improvement in OSS+10 mean scores was significant ($P < .05$).

SEPARATE EAR AND BINAURAL TESTING

Results of statistical analysis suggested that preimplant scores for the “ear to be implanted” were significantly poorer than the nonimplanted ear ($P < .01$) ($n=8$, OSWph and OSWw; $n=9$, OSS-Live). Postimplant scores for the implanted ear exceeded preimplant scores ($P < .01$) for OSWph and OSWw and OSS-Live. There was no significant change from preimplant scores to postimplant scores for the nonimplant ear (OSWph, $P = .06$; OSWw, $P = .87$; OSS-Live $P = .81$). Testing in the postimplant period indicated that the implanted ear scores exceeded those...
for the nonimplant ear (OSWph and OSWw, *P* < .01; OSS-Live, *P* = .01). The postimplant binaural scores exceeded preimplant binaural scores for OSS-Live (*P* < .01). Postimplant binaural scores for OSW testing were significantly better than monaural results with either cochlear implant alone for OSWph (Figure 3A) (*P* < .05) but not OSWw (*P* = .08) (Figure 3B). Postimplant binaural scores for OSS-Live were significantly better than monaural results with either cochlear implant alone (*P* < .01) or hearing aid alone (*P* < .01) (Figure 3C).

**SUMMARY**

Postimplant group means significantly exceeded preimplant group means for all 5 test materials/conditions, including OSWph (*P* < .001), OSWw (*P* < .001), OSS-Live (*P* < .001), OSS-Q (*P* < .005), and OSS+10 (*P* < .05). Postimplant performance for individual children also exceeded preimplant performance in all cases except subject 1 for OSWph, OSWw, and OSS-Live and subject 7 for OSS-Q. All 8 subjects tested with +10-dB competing noise improved their scores in the postimplant period. Postimplant binaural scores were significantly better than either cochlear implant or hearing aid alone for OSWph and OSS-Live.

**COMMENT**

Results from the present study suggest that children with useful auditory skills when using hearing aids may derive significant benefit from a cochlear implant in the poorer ear.

After only 6 months to 2 years' use of the cochlear implant (mean device experience, 1.14 years), postimplant speech perception group means exceeded preimplant group means for this group of 16 children. The mean postoperative scores were above 50% correct on all test measures, and in 3 of the 5 test measures (OSWph, OSS-Live, OSS-Q) they were above 75% correct. When averaged across all test measures the group mean scores improved by 34 percentage points. The difference in preimplant to postimplant percentage points was as follows: OSWph, 25.6; OSWw, 30.6; OSS-Live, 33.4; OSS-Q, 48.7; OSS+10, 38.0.

It is worth comparing the speech perception results for the children in this study with other groups of implant users. Results for an unselected group of 70 children from Melbourne, Australia, receiving implants between 1994 and 2000 showed mean scores for OSWw and OSS-Live of 28.8% and 56.0%, respectively, compared with 51.5% and 87.3% for the present study. The children in the present study also obtained a higher mean score than a group of 109 adults with postlingual onset of hearing loss and preimplant significant residual hearing. Results for the adult group for OSWw showed a mean score of 40.5% vs 51.5% in the present study; for OSS-Q a mean score of 80.4% vs 85.4%, and for OSS+10 a mean score of 49.9% vs 61.7%.

These comparisons, although only for a relatively small number, suggest that children with significant residual hearing before implantation can be expected to attain better speech perception performance than other groups of implant users.

The results of the present study suggest that 8 subjects tested with OSW and 9 subjects tested with OSS were able to combine the input from 2 different devices to per-

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**Figure 3.** Preimplant and postimplant mean binaural, cochlear implant (CI) alone, and hearing aid (HA) alone group scores for open-set word testing, scored for phonemes correct (A; n=8); open-set word testing, scored for words correct (B; n=8); and open-set sentence testing using live voice presentation (C; n=9). Duration of implant use for each subject is given in the Table. BKB indicates Bamford-Kowal-Bench sentences.
form significantly better than when they used either ear alone.

Traditionally, arguments used to encourage use of the contralateral hearing aid after implant have included the concept of “preserving” the nonimplanted ear from the degenerative effects of auditory deprivation. It is assumed that this ear may then yield a better result if it is implanted with more advanced technological systems in the future. This advice has been given with evidence from hearing aid studies but, to date, few studies have examined bilateral-bimodal device use for children.46-50 The results from the present study would also support ongoing contralateral use in the postimplant period. The subjects in the present study demonstrated binaural advantage when listening in quiet and in situations of coincident background noise. Further work is required to determine whether these improvements are due to overall loudness summation, or spatial or spectral cues afforded by the 2 devices. In addition, the potential advantages of binaural hearing for localization and for selectively attending to the ear providing a better signal (head shadow effect) require further investigation for this pediatric group.

Postoperative binaural scores on OSW/ph and OSSLive were significantly better than monaural scores with either the cochlear implant or hearing aid alone. This result is consistent with previous research that suggests that children with profound hearing loss who use an appropriately fitted hearing aid in the contralateral ear to their implant obtained significant benefits in speech perception, localization, and aural/oral function compared with their use of a cochlear implant alone.50 The subjects in the study by Ching and colleagues50 had, on average, less residual hearing in their hearing aid ear than the subjects in the present study.

Figure 2A indicates ceiling effects for 10 of the 16 children who obtained greater than 90% following implantation. Testing under more adverse conditions with competing noise is likely to give more useful information regarding postimplant performance. Because of clinical constraints and difficulties in testing young children, not all conditions were completed for all children. It can be difficult to encourage young children to complete open-set sentence lists in more adverse listening conditions. Protocols need to be established so as to obtain more complete data for these children before and after implantation, including assessments in situations of background noise and at regular intervals (eg, 6, 12, 18, and 24 months) postoperatively. This will enable research groups to make better comparisons across clinics and enable clinicians to provide information to parents to facilitate decision making.

Although not specifically reported in the present study, all children completed formal language measures such as the Peabody Picture Vocabulary test and Clinical Evaluation of Language Fundamentals. Following guidelines suggested by 2 articles published by Dowell and colleagues12,52 in 2002, the child’s duration of deafness, preimplant open-set sentence scores and language skills were considered as part of the child’s preimplant assessment. Children in the present study all presented with levels of spoken language at or greater than 5 years on the above-mentioned language tests. The correlation between language skills and speech perception for children with hearing aids and cochlear implants is well established.33 Future research is needed to determine whether duration of profound deafness, preimplant speech perception, and language abilities are associated with effective postimplant speech recognition for children combining the auditory input from hearing aids and cochlear implants.

It is likely that speech perception scores will continue to improve with greater device experience, as noted for other pediatric implant users.94-55 Further study should examine the child’s device experience, language skills, functional abilities outside the implant clinic, and optimum hearing aid fitting with a larger subject group. In addition, testing of the present group with spatially separated as well as coincident competing noise is warranted to address potential localization and head shadow effects for this group.

The results of this study support expanding the cochlear implant candidacy criteria to include selected children with significantly more residual hearing than is currently advocated. These candidates exhibited an asymmetrical hearing loss with open-set sentence scores of above 30% and up to 87% in the better ear or best binaural condition with live voice presentation, but had significantly poorer hearing in the contralateral ear. Although these children performed well in open-set speech perception tests in the clinic, their poor hearing in the contralateral ear resulted in difficulty understanding speech in their everyday environments. None of the children who proceeded with the cochlear implant obtained greater than 52% preimplant scores when tested with sentence material and competing multitalker babble—the mean score being 28%. The 2 highest scoring subjects for the preimplant OSS-Q and OSS+10 conditions also had a significant difference between PTA for the left and right ears. That is, both subjects had a clearly worse PTA ear (subject 1: implant ear, 123 dB HL; nonimplant ear, 73 dB HL; subject 14: implant ear, 115 dB HL; nonimplant ear, 97 dB HL).

The preimplant speech perception scores recommended above are proposed as a guide for implant centers, and, as always, each child’s candidacy should be determined with care, on an individual basis. Counseling should include preimplant contact between families to discuss the potential risks vs benefits and should include discussion regarding the length of time the child may require postimplant before he or she effectively combines bilateral-bimodal input.

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Acknowledgments to the speech pathologists and audiologists at the Cochlear Implant Clinic, Royal Victorian Eye and Ear Hospital, East Melbourne, Australia.

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