Outcomes for Cochlear Implant Users With Significant Residual Hearing

Implications for Selection Criteria in Children

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Objectives: To develop an evidence-based technique for providing recommendations to candidates for cochlear implantation with significant residual hearing and to assess the efficacy of the approach.

Design: Modified selection criteria were derived from an analysis of the postoperative performance for a large group of adult cochlear implant users. In particular, the distributions of results for implant users with significant preoperative open-set speech perception were reviewed. This suggested that the candidates had a good chance (>75%) of overall improvement if they obtained open-set sentence scores in quiet of up to 70% in the best-aided condition and scores of up to 40% in the ear to undergo implantation.

Patients: A group of 45 adult implantation candidates who fit the modified criteria and who underwent preimplantation and postimplantation assessment to compare actual results with those predicted from the distributions.

Results: The speech perception results showed that 36 subjects (80%) had improved open-set sentence scores with the cochlear implant compared with their best-aided preoperative performance (mean improvement, 20.5%). Forty-four (98%) had improved open-set sentence scores for the ear undergoing implantation (mean improvement, 65.3%).

Conclusions: The general concept of using the distribution of speech perception results to make evidence-based recommendations for candidates for cochlear implants is supported by this study. The approach can be used across different subpopulations, including older children with significant residual auditory skills, and for different outcome measures. It is important that the data used to provide recommendations and modify selection criteria are from an unselected sample of implant users of adequate size. This study highlights the continuing need to evaluate speech perception performance carefully before and after cochlear implantation.


Increasing numbers of patients referred to cochlear implantation centers are hearing-impaired children and adults with significant residual hearing.1,2 The improvement in cochlear implant technology and positive outcomes have encouraged users of hearing aids to consider the implantation procedure for improving their auditory skills. It is important, however, to keep expectations in context and to provide recommendations based on solid evidence wherever possible.

The outcomes of cochlear implantation have been impressive, particularly for certain populations, but there continues to be a wide range of performance, owing to factors that remain largely unknown or unmeasurable.3,4 Many studies have demonstrated that a number of factors have predictive value for outcomes in adults and children, but these factors account for considerably less than 50% of variance in scores.3,5-8

The cochlear implant specialist is faced with a difficult task in counseling candidates with significant residual hearing. A good cochlear implant outcome (ie, a result above the median performance) is likely to provide benefit to a large proportion of candidates with severe hearing loss. On the other hand, a poor outcome may lead to a decrement in auditory skills for some candidates. Clinical experience suggests that this scenario is rare, but even a small number of such cases could lead to serious consequences for a clinical program.

We need to know, at least approximately, how likely certain outcomes are for different populations so that patients and their families can make an informed decision and be aware of all possibilities.
This report presents a simple statistical approach to this problem that draws on postoperative outcome data for relatively large numbers of cochlear implant users. The approach relies on having this data available for all patients in a particular program (or at least an unbiased sample). It is clear that this information is not always available for every clinical program, particularly one that is small or in its infancy. Nonetheless, a consistent approach to assessment for all patients should be encouraged whenever possible so that candidates can receive realistic advice.

An important reason for the provision of evidence-based recommendations is that many cochlear implantation candidates with residual hearing have useful communication skills, at least in face-to-face conversation. They are not in the situation of traditional implantation candidates who tended to have very little hearing and not much to lose. Many recent candidates have useful auditory skills that could be lost if their cochlear implant procedure results in a poor outcome. Such poor outcomes are rare but can occur owing to unforeseen medical problems or anatomical variations, undiagnosed retrocochlear pathology, personality or psychiatric disorders, and occasionally no apparent reason. For a totally deaf patient, a poor outcome is disappointing, but to someone who had adequate communication with hearing aids and lip-reading, this could be devastating. If hearing is lost in the ear undergoing implantation (hereafter referred to as the implanted ear), there is a loss of perceptual ability for that ear and any existing binaural advantage. If the better ear undergoes implantation, the perceptual abilities may be decreased significantly from the preoperative situation. The decision-making process for most implantation candidates at present needs to address the probabilities of improvement and the worst-case scenario.

The average outcome for patients undergoing implantation does not provide particularly useful information for candidates. The distribution of speech perception abilities is extremely wide and, for many of the common assessments, does not represent a normal distribution. For instance, on open-set sentence material, a typical mean score for adult implant users with postlingual deafness is 80%, but very few subjects score close to 80%. This average represents a large proportion of patients scoring close to 100% and a small number scoring at lower levels, including 0%. Giving a candidate the expectation of obtaining speech perception at the 80% level is unrealistic. It is the distribution of these results that is more important in providing recommendations to candidates with residual hearing. The following is the real issue: “If my current speech perception ability is X, what are the chances that it will be greater than X if I decide on a cochlear implant?” It is also of interest to estimate the chances that speech perception may be worse than X.

The distribution of perceptual skills across all implantation patients is so wide that, without additional information, it is only possible to give candidates a rough idea of probabilities of outcomes. Research studies, however, have indicated how this process can be refined. Many studies have considered possible predictors of performance in adult and child cochlear implant populations. Duration of profound deafness has been consistently identified as having a significant negative correlation with outcomes. Other studies have suggested that age can also have a small but significant effect. Recently, residual hearing before implantation has been identified as an advantage to cochlear implant users. Also, little doubt remains that a prelingual onset of significant hearing loss can have a negative influence on outcomes for adults and older children. We can use some of these factors to refine the process of predicting outcomes for older children and adult candidates.

## METHODS

### ANALYSIS OF ADULT SPEECH PERCEPTION DATA

Adult patients undergoing implantation in Melbourne, Victoria, underwent assessment for speech perception ability before and after the procedure. The battery of tests included open-set sentence testing (City University of New York [CUNY] sentences), open-set monosyllabic word testing (consonant-nucleus-consonant [CNC] words) scored on the basis of phonemes and words correct, and open-set sentences in background noise at +10-dB signal-noise ratio. Preoperative testing aimed at making recommendations regarding implantation will generally involve separate ear and binaural testing when there is useful residual hearing in both ears. Postoperative assessments were performed in the first month after surgery, approximately 3 months after implantation, and at 12 months after implantation. To review the effect of previously identified predictive factors, we analyzed results for 262 adult patients at the 3-month evaluation using multivariate statistical techniques. This group included all patients undergoing implantation in Melbourne who had used the Spectral Peak or Advanced Combination Encoder signal coding in the Nucleus device (Cochlear Pty Ltd, Sydney, Australia) (including the CI 22 and CI 24 straight and curved electrode arrays). We excluded non–English-speaking patients and those who never used the implant device owing to medical, surgical, or psychiatric complications. Otherwise, this group represented a consecutive series of adult implant recipients from 1994 to 1999.

Postoperative speech perception results for monosyllabic words (CUNY sentences) and CNC words were arcsine transformed and submitted to separate multiple regression analyses using the following predictor variables: (1) duration of bilateral profound hearing loss in years, (2) preoperative pure-tone average hearing loss in decibels, (3) age at implantation in years, (4) preoperative open-set speech perception (1 if sentence score >10%; 0 if otherwise), and (5) prelingual onset of bilateral hearing loss (1 if onset at younger than 3 years; 0 if later).

### GROUPING OF ADULT IMPLANTATION CANDIDATES

Based on the findings of these analyses, we proposed the following 3 adult candidate groups: (1) prelingual onset, defined as those with onset of significant hearing loss (moderate or greater) before 3 years of age; (2) postlingual onset with poor auditory skills, defined as adults with onset of significant hearing loss after 3 years of age and speech perception scores of less than 10% for open-set sentences in the best aided condition; and (3) postlingual with significant auditory skills, defined as adults with onset of significant hearing loss after 3 years of age and speech perception scores exceeding 10% for open-set sentences in the best-aided condition.

The distributions of speech perception results for each group of adult implant users were reviewed. In particular, the
medians and lowest quartiles of the distributions for the standard battery of tests were determined for each group and each test. These details are shown in Figure 1. The groups included 103 postlingual implant users with poor preoperative auditory skills, 109 with significant open-set sentence scores, and 50 with prelingual onset of significant hearing loss. A clear difference was evident for the prelingual-onset group compared with the other 2 groups. This finding highlights the need for expectations to be maintained at a lower level for implantation candidates in this category. Small but significant differences were also evident between the postlingual-onset groups with and without residual auditory skills.

The median scores for these distributions give an estimate of expected outcomes for these patient groups, but it is the lowest quartile scores that provide perhaps the most useful information in counseling implantation candidates. If a candidate’s best preoperative aided speech perception scores fall below the lowest quartile of the appropriate distributions, the probability of improvement with a cochlear implantation procedure can be estimated as greater than 75%, as this proportion of scores lies above the lowest quartile. This approach can be used for the range of speech perception tests performed and for each of the patient groups. In particular, this information is important for those with significant residual hearing and speech perception skills.

The remainder of this report will focus on the residual hearing group and consider a modification of selection criteria in terms of open-set sentence scores. However, we must emphasize that this approach can and should be used across a variety of tests. Figure 2 shows the actual distribution of open-set sentence scores for the group of postlingual-onset hearing-impaired adults with residual auditory skills. The lowest quartile point for this distribution is noted.

MODIFIED SELECTION CRITERIA

Based on the data available from the Melbourne clinic (Figures 1B and 2), the lowest quartile score on the open-set sentence distribution for patients with residual hearing was 70%. Candidates with open-set sentence scores below this level in their best-aided condition were estimated to have at least a 75% chance of overall improvement with the use of a cochlear implant. It is important to ensure that the fit of the hearing aid is optimized and that left, right, and binaural testing is completed when there is residual hearing in both ears. This ensures that the best possible performance is captured and gives a comparison of the ears in terms of speech perception to add to audiometric data. In some cases, a hearing aid trial may also be appropriate.

The next step was to consider the ear that is likely to undergo implantation. Many factors may contribute to this decision, including the amount of residual hearing in each ear, the suspected cause of hearing loss, imaging of the cochleas and other temporal bone structures, the duration and onset of hearing loss in each ear, and, importantly, the patient’s preference once all available information has been provided.

Although arguments can be made to consider the better hearing ear for implantation surgery, candidates with sentence perception scores of up to 70% generally rely on their hearing for communication, and hence have a great deal to lose if implantation results in a poor outcome. To factor this into the modified selection procedure, it was suggested that the maximum sentence perception score for the ear to undergo implantation should not exceed 40%. Based on the distribution of scores for the appropriate implantation group (Figure 2), the chance of an outcome after implantation where sentence scores are below 40% is very small (<3%).

In summary, the modified selection criteria specified 70% as the maximum sentence score in the best, optimally aided condition, and 40% as the maximum sentence score for the ear that would undergo implantation. Candidates who fit these criteria could be advised that they had more than a 75% chance of improving their speech perception with a cochlear implant over their best preoperative condition, and a 93% chance of improvement in their implanted ear.
Prospective Analysis of Speech Perception for Residual Hearing Group

From July 1999 to June 2002, the modified criteria for implantation were used within the Melbourne clinical program. A total of 45 adults with postlingual hearing loss who had preoperative speech perception scores ranging from 40% to 70% in the best-aided condition underwent implantation. In all cases, these adults received the implant in the ear with poorer speech perception, satisfying the criterion that the implanted ear should have sentence perception of less than 40%.

Results

Multiple Regression Analyses for 262 Adult Implant Users

The following variables were found to have significant association with postoperative speech perception results for open-set sentences and monosyllabic words and sentences in competing noise:

1. Prelingual or postlingual onset of significant hearing loss (defined as onset of moderate, severe, or profound bilateral hearing loss before 3 years of age). Postlingual-onset patients showed better performance.
2. Duration of severe or profound hearing loss. Shorter duration was associated with better performance.
3. Age at implantation. Younger patients showed better performance.
4. Preoperative auditory skills (defined as open-set sentence scores >10% when using hearing aids). Those with significant open-set speech perception before implantation performed better.

Although these significant effects were consistent across tests and were consistent with findings in previous studies, only a relatively small proportion of variance in scores was accounted for by these factors (21%–31% of the variance). This suggests that the ability to predict outcomes for an individual patient from knowledge of these characteristics remains relatively poor. On the other hand, these results show that the population of adult implantation candidates is not homogeneous, and that it is appropriate to consider some groups of patients separately when making recommendations.

The regression equations obtained for the analyses of speech perception data along with other relevant statistics are shown below. The Table shows the t statistics and significance levels for the predictor variables in each analysis, using the following equations:

1. CUNY Sentence Score = 2.9 − [0.011 (Age at Implantation)] + [0.014 (Duration of Deafness)] − [0.91 (Prelingual Onset)] + [0.27 (Preimplantation Open-Set Ability)],

   where F = 22.5 (P < .001), with regression accounting for 31% of variance.

2. CNC Phoneme Score = 2.2 − [0.068 (Age at Implantation)] + [0.0088 (Duration of Deafness)] − [0.48 (Prelingual Onset)] + [0.16 (Preimplantation Open-Set Ability)],

   where F = 14.1 (P < .001), with regression accounting for 22% of variance.

3. CUNY Sentences at 10-dB SNR = 2.5 − [0.018 (Age at Implantation)] + [0.011 (Duration of Deafness)] − [0.94 (Prelingual Onset)] + [0.24 (Preimplantation Open-Set Ability)],

   where SNR indicates signal-noise ratio and F = 14.8 (P < .001), with regression accounting for 25% of variance.

   The interpretation of these regression equations is somewhat obscure, as they predict transformed scores between zero and π rather than percentage scores. Each equation, however, shows the same direction of effect for the predictor variables. There is a small negative effect as age at implantation increases and a similar effect for increasing duration of profound hearing loss. A prelingual onset of hearing loss has, on average, a substantial negative effect on these speech perception scores, and those with some open-set speech perception before implantation could expect higher scores than average.

   Figure 3 shows the actual phoneme scores for CNC words plotted against those predicted from the regression equation (after removal of the arcsine transform). The dashed lines represent a prediction interval containing 80% of the data points. The ability to predict speech perception outcomes accurately from this regression is limited, as the prediction interval is ±20% from the predicted score. For example, there is an 80% chance of a predicted score of 50% being in the range from 30% to 70%. The regression provides a ballpark estimate only.

Speech Perception Outcomes for Revised Criteria Group

The speech perception outcomes for the group of 45 adults with significant residual hearing were considered in terms of overall benefit from before to after implantation and

Table: Significance Levels for Predictor Variables for Multiple Regression Analyses on Speech Perception Scores for 262 Adult Cochlear Implant Users

<table>
<thead>
<tr>
<th>Speech Perception Test, Predictor Variable</th>
<th>t Statistic</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUNY Age at implantation</td>
<td>−3.18</td>
<td>.002</td>
</tr>
<tr>
<td>Duration of deafness</td>
<td>−3.33</td>
<td>.001</td>
</tr>
<tr>
<td>Prelingual onset</td>
<td>−5.52</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Preimplantation open-set ability</td>
<td>2.68</td>
<td>.008</td>
</tr>
<tr>
<td>CNC words (phoneme scores)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age at implantation</td>
<td>−2.76</td>
<td>.006</td>
</tr>
<tr>
<td>Duration of deafness</td>
<td>−2.91</td>
<td>.004</td>
</tr>
<tr>
<td>Prelingual onset</td>
<td>−4.11</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Preimplantation, open-set ability</td>
<td>2.25</td>
<td>.03</td>
</tr>
<tr>
<td>CUNY sentences at +10-dB SNR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age at implantation</td>
<td>−4.26</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Duration of deafness</td>
<td>−2.14</td>
<td>.03</td>
</tr>
<tr>
<td>Prelingual onset</td>
<td>−4.95</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Preimplantation open-set ability</td>
<td>2.03</td>
<td>.04</td>
</tr>
</tbody>
</table>

Abbreviations: CNC, consonant-nucleus-consonant; CUNY, City University of New York; SNR, signal-noise ratio.
benefit for the implanted ear. The results of these comparisons are presented in Figure 4. Figure 4A shows the improvement in open-set sentence scores in the implanted ear for each of the 45 patients. The postoperative scores in each case were obtained with the cochlear implant alone (ie, without the hearing aid in the contralateral ear). Figure 4B shows the comparison of postimplantation scores, obtained using the cochlear implant alone, with the best-aided result before implantation. The postimplantation results were obtained approximately 3 months after surgery.

All 45 adult implant users showed improvement in speech perception for the implanted ear (mean improvement, 65.3%). In 1 case, this improvement was less than 5%. Thirty-six patients showed better scores postoperatively with the cochlear implant than their best preoperative result for the nonimplanted ear (mean improvement, 20.5%). Nine (20%) of 45 had performance with the implant alone that was not as good as their best preoperative aided result.

Figure 5 shows the preimplantation and postimplantation median scores for this group of 45 adults with...
significant residual hearing on 4 speech perception measures. The postimplantation median scores are similar to those shown in Figure 1A for the larger group of adults with significant preimplantation speech perception.

This study has indicated that it is appropriate to use the distribution of speech perception results in implant users to advise potential candidates of their chances of improved auditory skills. In particular, we analyzed results for adults with significant residual hearing to provide expanded selection criteria for this population. For adults fitting the expanded criteria, we showed that outcomes, in terms of better overall speech perception and improvement for the implanted ear, were in line with predictions. That is, more than 75% of these candidates showed better speech perception with a cochlear implant than their best-aided preoperative condition, and more than 95% (44 subjects) showed improvement for the implanted ear. Also, no patient from this group had a decrement in their auditory skills as a result of implantation. In 80% of cases (35 subjects), implant-alone scores exceeded the best preoperative performance (Figure 4A). In the other 20%, the contralateral, better-hearing ear still provided the better speech perception (Figure 4B), but the implanted ear performance was improved.

For children with significant residual hearing who are old enough to undergo formal speech perception testing, the approach outlined in this report is appropriate. As more data are collected, the distribution of results for this group will provide a basis for quantifying recommendations. At this stage, there is not a large enough group of older children to quantify the distributions of scores in the same way as for adults, but results for this group have been encouraging for implant-alone performance and bimodal performance in conjunction with a contralateral hearing aid.

In essence, the approach described in this report amounts to a formalization of the concept of clinical experience without the biases that can sometimes influence even the most careful clinician. A multitude of factors peculiar to each individual candidate remain that will come into play during the recommendation and decision-making process. The statistical process discussed herein cannot substitute for the skills and judgment of an experienced implantation team. It can, however, bring a level of quantification to the process of counseling cochlear implantation candidates.

In reviewing the distributions of results for different groups of implant users, it is clear that a wide range of performance is possible for all groups. Despite the intuitive arguments and evidence that those with significant residual hearing perform at a higher level, this study indicates only marginally better scores than for those with poor preoperative auditory skills. Even when other variables such as duration of deafness and age are factored in, it remains difficult to predict outcomes accurately. It appears that there are factors relating to the functional state of the peripheral and central auditory system that are not easily assessed with current preoperative evaluations.

Blamey and colleagues have suggested that the state of the peripheral auditory system in terms of spiral ganglion survival may not be crucially important to cochlear implantation outcomes. They found that the pattern of outcomes in adult cochlear implant users was not what would be expected if spiral ganglion cell survival was the dominant factor, and argued that central factors also played a crucial role. There might be interactions between the type and extent of damage within the cochlea and the survival of spiral ganglion cells that limit the information flow at the electroneural interface. Further research is needed that combines electrophysiological measures with psychophysical and speech perception measures to provide more information in this area. Until we understand more precisely what is happening within the cochlear and central auditory systems for individual implant users, outcomes will probably remain unpredictable to a certain degree. The general approach put forward in this report offers a way of dealing with this lack of predictability and making realistic recommendations for individuals.

We used open-set, auditory-alone testing with CUNY sentences as the outcome measure to describe the distribution of results. The reasons for using this particular measure were largely historical, as this type of testing has been commonly used for assessment of implant users for more than 20 years. More complete data for various groups of implant users tend to be available preoperatively and postoperatively. During the 1980s, as speech processing for cochlear implant systems developed rapidly, this type of testing using CID (Central Institute for the Deaf), BKB (Barnford, Kowal, and Bench), and CUNY sentences provided a metric that covered the range of performance adequately. During the past 10 to 15 years, however, there has been an increasingly prominent ceiling effect on these tests for cochlear implant users. For instance, the distribution of results shown in Figure 2 indicates that half of the group scored above 91%. The assessment therefore fails to distinguish between the auditory skills of a large proportion of patients clustered near 100%. It also creates a nonnormal distribution of results, which makes the application of parametric statistics problematic.
For these reasons, it is essential that additional tests are used in the assessment battery to provide an appropriate match to the range of auditory skills for individual cochlear implant and hearing aid users. The approach described in this report has been applied in Melbourne to scores for monosyllabic words and sentences in competing noise, both of which provide more difficult tests of speech perception. In this way, the preoperative scores for a number of measures can be compared with median and lowest quartile points for postoperative distributions.

It remains important that results are collected on as large a sample as possible and the sample is free of any selection bias. Selection bias can easily extend into a set of clinical speech perception scores, as testers can be reluctant to put patients through a test procedure when they believe they will perform poorly. Over time, this attitude will result in only the better performers being tested, and the poorer results will not appear in the distribution of scores. This will give a favorable skew to the distributions and make the application of selection criteria based on them misleading.

This study of speech perception in a group of adult implant users with significant residual hearing has demonstrated the applicability of simple statistical techniques to providing recommendations to implantation candidates. The review of data from the Melbourne clinic showed that postlingual-onset hearing-impaired adults with useful speech perception before implantation were likely to benefit from cochlear implantation when open-set sentence perception scores were as high as 70%. Continuing assessment for all implantation candidates before and after surgery is essential to build an accurate picture of the distribution of scores and enable the formulation of appropriate selection criteria. A similar approach can be applied for older children with residual hearing who are considering cochlear implantation. Although open-set sentence scores have been highlighted in this study, a battery of tests is needed to provide for the wide range of auditory skills and avoid floor and ceiling effects.

Submitted for publication September 10, 2003; final revision received November 13, 2003; accepted November 17, 2003.

This study was presented at the Ninth Symposium on Cochlear Implants in Children, April 24, 2003, Washington, DC.

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