Predictive Models for Cochlear Implantation in Elderly Candidates

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Objective: An aging American population carries a high prevalence of profound sensorineural hearing loss. We examined the performance of multichannel cochlear implant recipients in a large database of adult subjects.

Design: Nonconcurrent prospective study of a national cohort with multivariate regression analysis of preoperative and postoperative performance variables in multichannel cochlear implant recipients. We applied models of prediction established in previous studies to the observed results.

Setting: Referral centers with active cochlear implant programs.

Patients: Adolescents and adults with profound hearing loss (N=749; age range, 14-91 years).

Main Outcome Measure: Postoperative monosyllabic word recognition.

Results: The population 65 years and older demonstrated a clinically insignificant 4.6%-smaller postoperative word score compared with the population younger than 65 years. When duration of deafness exceeded 25 years, elderly recipients demonstrated higher word scores than their younger counterparts. A more significant factor affecting outcomes is the ratio of duration of deafness to age at implantation.

Conclusions: Age at implantation carried relatively little predictive value for postoperative performance in subjects 65 years and older. Although a small decrement in mean speech recognition scores was evident, the clinical significance of this difference is questionable when all of the results observed in elderly patients are considered. A shorter percentage of life spent in severe-to-profound sensorineural hearing loss suggests a foundation of acoustic/auditory processing in the elderly cohort that may mitigate potential physiological effects associated with advanced age. This study confirms and extends previous observations that duration of profound deafness and residual speech recognition carry higher predictive value than the age at which an individual receives an implant.


Hearing impairment is a significant and commonly encountered problem in the elderly population. Of the 35 million people 65 years and older in the United States,1 from 250 000 to 400 000 have severe to profound hearing loss.2,3 Age-related hearing loss is known to contribute to age-associated disease burden. Psychological disturbances,4 social and emotional handicaps,5,6 and significant reductions in mental and physical functioning7 are known to be associated with advanced levels of sensorineural hearing loss in elderly patients. A question of growing importance is whether cochlear implantation can address these concerns for elderly patients. Cochlear implantation candidacy in this subset of candidates should be considered in light of observed results and predictors of outcome.

Cochlear implantation has become a popular method of treatment for hearing loss, but despite numerous studies indicating benefit,8-12 the procedure remains controversial when applied to elderly patients. Although impressive improvements in hearing abilities, emotional health, and quality of life can certainly be achieved, these gains are weighed against surgical risks and cost-utility ratios.

Complicating the matter are issues of health care rationing. Given their growing proportion of the population, elderly patients with hearing loss represent potentially considerable costs in reimbursements for the implantation process. An important concern raised by payers is that emerging technologies such as cochlear...
im implantation are too often applied to entire populations within a disease category without selecting the best candidates. Precisely determining who will best benefit from a cochlear implant is a key goal for current implant research.

Studies identifying predictive factors for implantation outcomes have mainly focused on patient, ear, and device variables. Rubinstein et al.13 found that duration of deafness and preoperative Central Institute for the Deaf (CID) sentence understanding scores carry the most significant predictive validity of all variables and can account for a large percentage of the variability in results. Friedland et al.14 also found duration of deafness to be the strongest predictor of outcome. Regression analyses from Rubinstein13 and Friedland14 et al demonstrate the following model of prediction for speech recognition results:

\[
\text{Postimplantation Word Score} = A - (B \times \text{DUR}) + (C \times \text{CID}) - \{D \times \lbrack \text{DUR} / (1 + \text{CID}) \rbrack\},
\]

where DUR is duration of deafness in years, CID is preoperative CID sentence understanding score, and A, B, C, and D are constants that are valued to best fit the observed postimplantation word score with the known duration of deafness and preoperative sentence score. The greater the duration of deafness and the lower the lower the preoperative sentence understanding scores, the lower the postimplantation word score. Both studies13,14 demonstrate that B is greater than C, indicating that duration of deafness carries even greater predictive value than the preoperative CID sentence understanding score. We investigated how this formula applies to populations 65 years and older and the effect of advanced age on hearing outcomes.

Past efforts to determine age effects have largely been hampered by small sample sizes. Statistical modeling used by Rubinstein13 and Friedland14 et al offers perspectives that may inform clinical predictions of outcome and guide the development of selection criteria. This report attempts to clarify implantation in elderly patients by applying these methods to a large national cohort undergoing implantation at all ages in adolescence and adulthood.

### Table. Characteristics of Population

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>&lt;65 y (n = 491)</th>
<th>≥65 y (n = 258)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age at implantation, y</td>
<td>43.9 (12.0)</td>
<td>73.4 (5.6)</td>
</tr>
<tr>
<td>Range</td>
<td>14-64</td>
<td>65-91</td>
</tr>
<tr>
<td>Duration of deafness, mean (SD), y</td>
<td>16.0 (16.1)</td>
<td>13.3 (16.4)</td>
</tr>
<tr>
<td>Preoperative CID sentence score</td>
<td>21.0 (29.1)</td>
<td>24.5 (29.3)</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>21.0 (29.1)</td>
<td>24.5 (29.3)</td>
</tr>
<tr>
<td>Range</td>
<td>0-100</td>
<td>0-100</td>
</tr>
<tr>
<td>Preoperative CNC word score</td>
<td>40.0 (42.3)</td>
<td>17.0 (23.4)</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>40.0 (42.3)</td>
<td>17.0 (23.4)</td>
</tr>
<tr>
<td>Range</td>
<td>0-100</td>
<td>0-98</td>
</tr>
</tbody>
</table>

**Abbreviations:** CID, Central Institute for the Deaf; CNC, consonant–nucleus consonant.

### METHODS

**PATIENT POPULATION**

The subject pool consisted of 749 adolescents and adults with profound hearing loss who underwent implantation with multichannel cochlear implants at The Johns Hopkins Hospital, Baltimore, Md, and in 2 clinical trials at the Cochlear Corporation, Englewood, Colo, and Advanced Bionics, Sylmar, Calif. The cohort consisted of 416 patients from The Johns Hopkins Hospital, 59 from the Cochlear Corporation, and 274 from Advanced Bionics.

The difference between baseline performance and performance within the first year of implantation constituted the primary outcome variables. We recorded the following variables: age at implantation, age at total deafness, duration of deafness (defined as the difference between age at implantation and age at total deafness), preoperative CID sentence scores, preoperative consonant–nucleus consonant (CNC) word scores, and postoperative CNC word scores (defined as the best score on any test within the first year after implantation). Preoperative CID sentence scores and postoperative CNC word scores were used to avoid floor and ceiling effects. Postoperative CNC word scores were used as the outcome measure. For patients from the Cochlear Corporation database, preoperative City University of New York sentence scores were substituted for CID sentence scores.

The Table describes the key features of the population. Age at implantation ranged from 14 to 91 years. Based on federal policies defining the elderly, 65 years of age was used as a boundary to divide the cohort into 2 comparison groups. There were 258 patients 65 years and older and 491 patients younger than 65 years. The mean age at implantation was 43.9 years for the younger cohort and 73.4 years for the older cohort. The mean duration of deafness was 16.0 years for the younger cohort and 13.3 years for the older cohort. The mean preoperative CID sentence score was 21.0% for the younger cohort and 24.5% for the older cohort. The mean preoperative CNC word score was 40.0% for the younger cohort and 17.0% for the older cohort.

**FORMULAE**

The mathematical analysis performed in this study was based on 2 previous studies by Rubinstein13 and Friedland14 et al. Their models predicted postoperative CNC word score (pCNC) using duration of deafness (DUR) and preoperative CID sentence scores (CID) using the following equations:

\[
p_{\text{CNC}} = 53.9 - \{0.42 \times \text{DUR}\} + \{0.13 \times \text{CID}\} - \{0.77 \times \lbrack \text{DUR} / (1 + \text{CID}) \rbrack\}
\]

for Rubinstein et al and

\[
p_{\text{CNC}} = 49.73 - \{0.56 \times \text{DUR}\} + \{0.34 \times \text{CID}\} - \{0.45 \times \lbrack \text{DUR} / (1 + \text{CID}) \rbrack\}
\]

for Friedland et al.

Although the constants differ between the 2 polynomial equations derived from the observed data, the equations reflect similar factors that carry predictive strength (DUR and CID) and, of these 2 factors, relatively greater impact is carried by DUR.

### STATISTICAL ANALYSIS

To verify the applicability of a previously established mathematical formula predicting postoperative CNC word score to populations including the elderly, we performed multiple regression analyses using duration of deafness, preoperative CID sentence scores, and age at implantation as independent variables. A model comparing the cohort younger than 65 years with the cohort 65 years and older was also generated using a
similar formula, with duration of deafness, preoperative CID sentence score, and a binary indicator dividing the 2 age groups as independent variables. Also included in these formulae was a compression factor using duration of deafness and preoperative CID sentence scores as variables. Bivariate scatterplots with regression fit compared the age at implantation, duration of deafness, and ratio of duration of deafness to age at implantation with the postoperative CNC word score. These tests were completed on StatView, version 5.0.1 (SAS Institute Inc, Cary, NC).

## RESULTS

### CORRELATION WITH AGE AT IMPLANTATION

**Figure 1** shows the postoperative CNC word score as a function of age at implantation. The scatterplot suggests large variability in the results, and a wide range of postoperative word scores were possible for any given age group. Consequently, the trend is virtually a straight line through the mean word score. Age at implantation accounted for 0.2% of the variance in word score, and the P value was .31, implying a statistically insignificant correlation.

### CORRELATION WITH DURATION OF DEAFNESS

**Figure 2** shows postoperative CNC word score as a regression on duration of deafness. When we took both age groups together, there was a general decrease in word score with increasing duration of deafness. However, when we divided the population according to their respective age groups, the decrease in word score associated with increase in duration of deafness was more significant in the group younger than 65 years (P<.001) than in the group 65 years and older (P=.13). Beyond a duration of deafness of approximately 25 years, the older cohort demonstrated better performance on average than the younger cohort.

### CORRELATION WITH RATIO OF DURATION OF DEAFNESS TO AGE AT IMPLANTATION

**Figure 3** shows the postoperative CNC word scores as a function of the ratio of duration of deafness and age at implantation. The effect was more profound in the younger portion of their lives deaf), postimplantation word score diminished. The effect was more profound in the younger group, however, with a P value of less than .001 (vs P = .10 in the older group). With a ratio of less than 2:3, the younger group appeared to perform better on average; this relationship reversed with ratios greater than 2:3.

## PREDICTIVE FORMULAE FOR POSTOPERATIVE OUTCOME

Based on the models of Rubinstein and Friedland et al, the following formula was generated for the cohort 65 years and older:

\[ p_{\text{CNC}} = 43.83 - (0.13 \times DUR) + (0.038 \times CID) - (0.22 \times \frac{DUR}{1 + CID}) - [0.005 \times (\text{Age at Implantation})] \]

For each year older than 65 years, the postoperative CNC word score decreased by a minimal 0.005%. The P value for the age variable was .99, suggesting a statistically insignificant effect on postoperative outcome. Unlike the previous models, duration of deafness and preoperative CID sentence score were not statistically significant in this age group (P = .32 and P = .59, respectively).

The following formula was generated for subjects of all ages:

\[ p_{\text{CNC}} = 47.57 - (0.21 \times DUR) + (0.082 \times CID) - (0.41 \times \frac{DUR}{1 + CID}) - [0.005 \times (\text{Age at Implantation})] \]

Again, as in the cohort including only those 65 years and older, each year of age took 0.005% away from the postoperative CNC word score. The P value for the age variable was .94, also suggesting a statistically insignificant effect. Unlike the model of Rubinstein et al, duration of deafness was a
significant variable ($P = .01$), but preoperative CID sentence score was not ($P = .08$).

The following binary model was also generated that compares the cohort younger than 65 years with the cohort 65 years and older:

$$pCNC = 49.08 - 0.22 \times DUR + 0.090 \times CID - [0.40 \times (DUR/1 + CID)] - (4.593 \times z),$$

where $z = 0$ if age is younger than 65 years and $z = 1$ if age is 65 years or older.

For patients with the same duration of deafness and CID sentence score, those undergoing implantation at 65 years and older had on average a 4.6% lower postoperative CNC word score compared with those undergoing implantation at younger than 65 years. Although the $P$ value of .04 may suggest statistical significance, whether this 4.6% decrease is clinically significant is debatable. In this equation, following the model of Rubinstein et al,13 duration of deafness and preoperative CID sentence score were both statistically significant ($P = .01$ and $P = .05$, respectively).

Results of this national cohort study demonstrate that age has a minimal effect on postoperative outcome for elderly recipients of cochlear implantation. Postoperative CNC word scores were widely variable across all age groups.

Results in this large national cohort concur with those of previous studies11,15,16 that demonstrated no statistically significant difference in CNC word scores after implantation between the cohort younger than 65 years and the cohort 65 years and older. However, other studies have shown less promising performance in older patients. A smaller cohort study12 showed significant improvement in the auditory abilities of implant recipients 70 years and older and that this group performed more poorly than the group younger than 70 years in CID sentence scores, Hearing in Noise Test sentences, and CNC words.

Numerous factors may contribute to the discrepancies in observed results with cochlear implantation. Variability in patient characteristics, testing methods, selection criteria, and the implant devices will affect observed results. Factors that are difficult to quantify such as cognitive ability and engagement with the rehabilitative program, as well as some degree of variability in true duration of deafness and residual hearing, may account for the observed difference in results. Psychological motivation and experiential background may also play a role in postoperative outcome. Patients may have varied in terms of the type of device implanted, the array, the processing strategy, and whether or not a hearing aid was used postoperatively in the contralateral ear. Future studies controlling for these factors may elucidate more specific predictors of postoperative performance.

In addition, study design may generate different conclusions. For example, the use of an age cut point of 70 years as a boundary between older and younger cohorts may have altered final conclusions.12 Significant differences between a population 70 years and older and a population younger than 70 years could be masked by this age grouping.

Whether improved postoperative CNC word scores or gains in CNC word scores translate into enhanced health-related quality of life is of significant importance in considering coverage of highly sophisticated implantable devices. Francis et al10 observed strong interactions between speech perception gains and improvements in quality of life and emotional well-being. Further study of indirect effects is needed to understand the impact of implant-mediated improvements in hearing on general health. For example, it is important to understand to what extent speech perception gains might contribute to improved social connectivity and the most cost-efficient use of health care services.

The mathematical models used in this study were based on those developed by Rubinstein13 and Friedland14 et al. An additional age factor added into their original predictive formulae for postoperative CNC word score demonstrated the negligible effect of age on implantation outcomes. For the population 65 years and older, each year older than 65 years decreased postoperative CNC word score by a clinically and statistically insignificant 0.005%. A similar result was achieved when all ages were grouped together. Although the cohort 65 years and older as a whole showed on average a 4.6%-smaller postoperative CNC word score compared with the cohort younger than 65 years, this discrepancy may be clinically undetectable.

Although Rubinstein et al13 and Friedland et al14 both illustrated the utility of a mathematical predictive model heavily based on duration of deafness and preoperative CID sentence scores, their derived formulae differed from those of the present study. Specifically, our coefficients for duration of deafness and preoperative CID sentence score were much smaller, and only in a binary model were both factors considered statistically significant. Moreover, our formulae did not account for the same 80% of the variance in word recognition that Rubinstein et al13 found. These discrepancies could be attributed to differ-

![Figure 3. Postoperative consonant–nucleus consonant (CNC) word score as a function of the ratio of duration of deafness to age at implantation. The thick gray line represents subjects 65 years or older (n=206; $P = .10$). The thin black line represents subjects younger than 65 years (n=315; $P = .001$). The negative prediction of the ratio on postimplantation word scores was more pronounced in the cohort younger than 65 years.](image-url)
ences between the 2 separate populations, particularly the testing methods and selection criteria.

However, the formulae indicated that even if not significant, duration of deafness and preoperative CID sentence score carry greater predictive value than age at implantation. In particular, duration of deafness had an impact on postoperative outcome, matching results found by Tyler and Summerfield. A longer duration of deafness was generally correlated with a lower postoperative CNC word score. A comparison of postoperative performance between the cohort younger than 65 years and that 65 years and older yielded an interesting trend, ie, for subjects with a duration of deafness beyond 25 years, higher CNC word scores were seen in the older group. This suggests that age alone cannot predict postoperative outcome and that advanced age is not necessarily correlated with poorer performance with a cochlear implant. Rather, the success of implantation appears to depend on additional variables, for instance, whether or not the patient had full access to critical phonologic information in developmental phases critical to language learning. One may logically propose that elderly patients with a short and recent duration of deafness will generally perform better than younger patients who have been deaf for their entire lives. More advanced language abilities and residual hearing capacity in the former group would allow them to perform just as well if not better than younger patients.

To investigate this notion further, this study probed the relationship between postoperative outcome and the ratio of duration of deafness to age at implantation. We asked how performance is affected by the percentage of life lived in deafness. This factor, first analyzed in detail by Tyler and Summerfield, is related to the DURAGE measure, the duration of deafness divided by patient age, first hypothesized by Shipp and Nedzelski as a predictive index. In this study, a greater ratio or percentage had a negative impact on performance with a cochlear implant, as patients who had spent a greater portion of their life in deafness had worse outcomes. This effect, however, was far more pronounced in the cohort younger than 65 years (P < .001), suggesting that younger patients who have spent most of their lives deaf may have outcomes similar to or even worse than those of older patients with the same histories. One drawback of this particular investigation, however, is that of the 212 patients 65 years and older, only 10 had a ratio of duration of deafness to age at implantation greater than 2:3, the ratio after which the older cohort appeared to perform better. Further investigation of elderly users of cochlear implants with longer duration of deafness would further clarify conclusions regarding elderly subjects with very-long-term deafness.

A foundation of central auditory processing in the older cohort may actually mitigate the disadvantages of advanced age at implantation, build on adaptive skills, and help to explain the encouraging results of this study. An auditory foundation is a form of cognition reflecting an internalized memory of the sounds of speech and the ability to process sensory inputs that are based in sound. The idea of retained auditory processing abilities in acquired deafness is not new. Kral et al found greater synaptic activity in infragranular cortical layers in electrically stimulated hearing cats compared with a deficit of activity in the naive auditory cortices of congenitally deaf cats. Engineer et al found stronger auditory cortex responses in rats with greater environmental enrichment. Salo et al found specific patterns of stable phonetic memory traces that remain even after a period of auditory inactivation in patients with cochlear implants.

With an auditory foundation, patients may maintain ongoing low-level activity or patterns of neuronal connection in the auditory pathway that can sustain physiological function. Such auditory experience may confer an advantage to elderly subjects, despite their long duration of deafness. They can then capitalize on their retained abilities to overcome the age-related degeneration of their auditory systems and surgical risks that would otherwise hinder their progress.

CONCLUSIONS

There is little reason to suggest that elderly patients with profound hearing loss are unsuitable candidates for cochlear implantation. This study illustrated that age has little predictive value in determining postoperative performance with a cochlear implant, as increasing age seems to have a negligible effect on postoperative word scores. Furthermore, patients 65 years and older perform similarly to patients younger than 65 years and may perform even better given certain durations of deafness. In fact, duration of profound deafness, along with the percentage of life lived deaf, hold greater predictive power than age, demonstrating that residual hearing capacity and language abilities may hold the key to postoperative success in the elderly cochlear implant recipient. Elderly patients should therefore not be discriminated against in assessments for cochlear implant candidacy.

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Announcement

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