Cochlear Implantation in Adults with Neurofibromatosis Type II: Outcomes, Benefits, and Limitations

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Cochlear Implantation in Adults with Neurofibromatosis Type II:
Outcomes, Benefits, and Limitations

By
Lydia Riehl

A capstone research project submitted to the Graduate Faculty in Audiology in partial fulfillment of the requirements for the degree of Doctor of Audiology,
The City University of New York 2017
This manuscript has been read and accepted for the Graduate Faculty in Audiology in satisfaction of the capstone research requirement for the degree of Au.D.

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ABSTRACT

Cochlear Implantation in Adults with Neurofibromatosis Type II: Outcomes, Benefits, and Limitations

By

Lydia Riehl

Advisor: Carol A. Silverman, Ph.D., M.P.H.

The objective of the current study was to examine, in a retrospective case series, outcome in terms of word-recognition performance in patients with neurofibromatosis Type 2 (NF2) who have received a cochlear implant (CI). The primary independent variables were duration of deafness (DoD) and age at cochlear implantation. The secondary independent variables were status of hearing sensitivity in the ear contralateral to the one that received cochlear implantation and the type of tumor treatment.

The retrospective case series comprised eight patients who were implanted at New York University Medical Center, or who were receiving follow-up care there. All NF2 patients in this study had an anatomically intact auditory nerve in the ear that was implanted, and were implanted unilaterally. The results post implantation revealed that all eight patients achieved an auditory percept and were daily users of a CI. Of the 8 patients, 87.5% (7 of 8) gained open-set speech-recognition ability. Additionally, 75% (6 of 8) of the patients were high performers, achieving open-set speech recognition greater than 66%. One patient was an intermediate performer (33% - 66%).

These findings were incorporated into data collected from other investigators, yielding a total of 36 patients with NF2 and an intact auditory nerve in the affected ear, and unilateral cochlear implantation. The findings based on this larger set of patients revealed that 92% were
daily users of the implant, and 67% (24 of the 36) achieved some degree of open-set speech recognition.

In conclusion, the results show that cochlear implantation can be a promising option for individuals with NF 2 who have an anatomically intact auditory nerve. No statistically significant relation was found between DoD or age at implantation and word-recognition scores post implantation. Therefore, it is difficult to predict, based on DoD or age at implantation, how well an individual with NF2 will do with his/her CI with regard to word-recognition performance; nonetheless, the probability of an auditory percept post implantation is high. Furthermore, the probability of gaining some degree of open-set speech recognition post implantation is somewhat greater than chance (about 60%).

**Key words:** Neurofibromatosis Type II (NF2), Vestibular Schwannoma (VS), Cochlear implant (CI), Duration of Deafness (DoD), open-set speech recognition
INTRODUCTION

Neurofibromatosis type 2 (NF2) is an autosomal dominant disorder resulting from mutations in both alleles of a tumor suppression gene on chromosome 22. Individuals with NF2 develop benign schwannoma tumors throughout the body. The most common tumors are spinal, intracranial, and on the vestibulocochlear nerve. The prevalence of NF2 is around 1:60,000 making it is a rare genetic disease (Evans, 2009). The age of onset usually is in early adulthood. Studies on the progression of NF2 have found the average age of onset to be about 20 to 25 years (Evans, 2009). Individuals who have NF2 with a more severe phenotype tend to have earlier onset of the disorder than individuals who have NF2 with a mild phenotype.

A hallmark of NF2 is vestibular schwannoma (VS) growth on both auditory nerves, occurring in 90-95% of patients (Roehm et al. 2012). The associated hearing loss, usually unilateral, is accompanied by tinnitus. The growth of these tumors eventually leads to bilateral sensorineural hearing loss, and often deafness. Vestibular symptoms, such as imbalance and dizziness, also can present as initial symptoms, but these symptoms often do not persist (Evans, 2009). Current management techniques for VS include surgical resection, stereotactic radiosurgery (e.g., gamma knife) and conservative monitoring (i.e., watchful waiting).

Otologists who perform surgical resection of VSs have become very skilled at preserving the anatomy of the vestibulocochlear and facial nerves; nonetheless, preserving hearing is very difficult to accomplish. The findings of previous investigations indicate that hearing preservation is possible in only 32 to 67% of patients; on the other hand, anatomical
preservation of the cochlear nerve is possible in approximately 80% of patients (Carlson et al., 2013). Aural rehabilitation for NF2 patients post tumor removal is a challenge because of the severity and nature of the hearing loss. Although VSs are benign, removal or radiation often is necessary to prohibit further growth into the internal auditory canal and damage to inner ear structures. Patients with NF2 often will develop severe to profound bilateral hearing loss after tumor treatment. Traditional options for these patients have included hearing aids and auditory brainstem implants.

Auditory brainstem implants (ABIs) bypass the vestibulocochlear nerve and directly stimulate the cochlear nucleus in the auditory brainstem using a series of electrodes. When introduced 30 years ago, ABIs became the first prosthetic device used in auditory rehabilitation of NF2 patients. Many medical and audiological professionals then presumed that an ABI was the only feasible option for these patients. Often, surgeons would place an ABI currently with resection of the VS if they felt that residual hearing could not be preserved during the resection (Carlson et al., 2013).

Investigators have compared outcomes of patients with NF2 who use a CI versus those with NF2 who use an ABI. The results indicate that open-set speech understanding is more probable in the former than in the latter (Vincenti, Pasanisi, Guida, Trapani, & Sanna, 2007). In many cases, the best achievable outcomes of an ABI include environmental sound awareness and assistance in lip-reading. In addition, CI surgery is more advantageous than ABI surgery. The former requires less time in the OR than the latter and is a more standardized procedure than the latter. Additionally, ABI surgery is much more complex and presents greater surgical risks than CI surgery (Vincenti et al.). The number of neurotologists who perform CI surgery greatly
exceeds that for those who do ABI surgery. Because of the many advantages of a CI, a patient who has an intact cochlear nerve and no contraindications should first consider CI surgery before considering ABI surgery, particularly as it is unlikely that the patient will develop speech recognition with an ABI. If a CI is unsuccessful, that is, it fails to produce sound awareness, then an ABI subsequently can be considered.

Over the past ten years, researchers at an increasing number of CI centers have studied the outcomes of patients with NF2 who receive a CI. In a multi-center retrospective study by Lustig et al. (2006), outcomes of seven patients with NF2 from Johns Hopkins, Mayo Clinic, and Stanford CI centers were examined. Of these seven patients, three had residual hearing in the contralateral ear and four had bilateral, severe to profound sensorineural hearing loss. All seven patients had auditory perception with the CI. Three of the seven patients with a CI achieved open-set speech recognition. Although the results may seem disappointing compared to the results in adults without NF2 who receive CIs, they were quite promising because every patient in this subset achieved auditory perception. All seven patients had VSs with attempted preservation of the cochlear nerve, and these results confirm that cochlear nerve function still exists for these patients and can be exploited.

Roehm et al. (2012), at the New York University Medical Center and Cochlear Implant Center, sought to determine whether 7 patients with NF2 who received a CI could obtain open-set speech recognition. Of the 7, 5 had the tumor surgically removed, 1 underwent radiation, and 1 one underwent monitoring for a small tumor. Of the 7, 4 achieved open-set speech discrimination, and 6 were daily users of the CI and felt that the CI was beneficial. Thus, Lustig et al. (2006) and Roehm et al. found that about 50% of patients examined achieved open-set
speech recognition. The more compelling case for implantation, however, was that in both studies, about 90% of patients reported subjective benefit from the CI and were daily CI wearers. Although the sample size of these studies is small, the results of these studies show promising benefit from cochlear implantation.

Perhaps the most comprehensive paper thus far on the topic is a retrospective case series and systematic review paper by Carlson et al. (2013). The case study comprised 10 patients ranging in age from 25 to 67 years. Of the 10, 5 underwent microsurgical resection of the ipsilateral tumor, 4 underwent stereotactic radiosurgery, and 1 underwent tumor monitoring. The duration of deafness (DoD) (the length of time that the hearing loss has been severe to profound in degree) among these patients ranged from 0 to 7 years. Additionally, one patient had significant ossification of the cochlea and another had tumor growth within the cochlea. Despite these additional symptoms, full insertion of the electrode array into the cochlea during cochlear implantation was achieved in all, and all were fit with the most up-to-date processor. Of these 10 patients, 9 achieved sound awareness, 6 achieved open-set speech recognition, and 7 were daily users of the CI.

Carlson et al. (2013) also evaluated the findings across the various investigators on all patients with NF2 who received a CI. Analysis of their systematic review, based on a total sample of 43 patients, including their 10 patients, revealed that open-set speech recognition was achieved in 65% of patients receiving surgical resection, 80% of patients who underwent stereotactic radiation, and in the 2 patients who were followed with conservative monitoring. The results trended toward better performance on open-set speech recognition for the patients receiving stereotactic radiation than for patients receiving surgical resection, but this finding
did not reach statistical significance. Notably, the sample size of patients receiving stereotactic radiation was much smaller (N = 10) than that for those receiving surgical resection (N = 31). The effects of variables such as DoD, promontory stimulation results, and contralateral hearing on speech recognition also were examined. The results revealed that patients with a DoD less than ten years were statistically more likely to achieve open-set speech recognition and have successful telephone usage than patients with a DoD greater than ten years. Overall, Carlson et al. found that prolonged auditory deprivation, cochlear ossification, unfavorable promontory stimulation, and useful contralateral hearing were associated with poor CI performance. Interestingly, the better a patient’s contralateral hearing sensitivity, the more difficulty the patient had in acclimating to the sound quality of the CI and in using it regularly.

Research on adults (non-NF2 etiology) receiving a CI has shown DoD to be a primary factor related to outcome. That is, the findings tended to reveal an inverse relation between DoD or magnitude of hearing loss, on the one hand, and speech-perception score, on the other hand. For example, Holden et al. (2013) reported that patients with a DoD not exceeding five years performed significantly better than those with a duration of deafness exceeding five years. The mean DoD in the study was 13.1 years. Some researchers also have demonstrated that age at cochlear implantation is a contributing factor to speech-recognition outcomes. Nonetheless, age at implantation is not a conclusive factor in speech-recognition outcome; rather, it is a variable to be considered in implantation.

A common theme within the literature on NF2 and CI is that although open-set speech recognition is not always possible—it is achievable in 50-70%—it is likely that such patients with an intact cochlear nerve at least will become daily users of a CI and report benefit from a CI.
The high probability of auditory percept, and significant possibility for speech recognition make a CI an appealing option for patients with NF2.

**Purpose:**

The primary purpose of this retrospective investigation is to examine auditory perception outcomes of eight patients with NF2 from New York University Cochlear Implant Center. Additionally, the data from these patients will be incorporated into Carlson’s et al.’s (2013) data set, so that outcomes also will be examined in this larger data set.
METHODS

Institutional Review Board (IRB) approval of this retrospective chart study was obtained from City University of New York and from the New York University Cochlear Implant Center. Under the IRB approval at the latter site, each patient had signed a formal agreement at the time of surgery to allow his/her data to be used for research purposes. The data were de-identified and were collected from the medical charts. Data on independent variables such as DoD, hearing-aid use in the contralateral ear, word-recognition performance pre-cochlear implantation, and on the dependent variable (word-recognition performance post cochlear implantation) were collected. The score on the dependent variable was based on performance on the Consonant-Nucleus-Consonant (CNC) word-recognition test. This medical chart review yielded data from 8 patients who received a CI at New York University Cochlear Implant Center from 1997 to 2016.

The data also were analyzed based on the data on 26 patients in Carlson et al.’s (2013) systematic review along with the eight patients unique to this paper from New York University Medical Center and Cochlear Implant Center. Thus, the number of patients in this larger data set was 36; the speech-recognition material that was common to all 36 patients was CNC words. Notably, Carlson et al.’s data set was based on 43 patients, but only 26 of these 43 patients were included for this study because those 26 patients had documented CNC word scores post-implantation. The independent variables examined included age at cochlear implantation, DoD, and status of hearing in the contralateral ear. The dependent variable was CNC score. Where available, sentence-recognition score also was examined. With regard to
open-set word- or sentence-recognition ability, patients were classified as high performing (67-100%), intermediate performing (34-66%), or low performing (0-33%).
RESULTS

New York University Cochlear Implant Center Data Set

For the smaller data set, based on the 8 patients (4 females and 4 males) with NF2 from New York University, who received a unilateral CI during the past 20 years, the median age was 50 years, with a range of 33 to 65 years. The median DoD in the implanted ear was 2.1 years, with a range of .42 years to 20.5 years. Figure 1 shows a histogram of the DoD among the 8 patients.

Figure 1. Histogram of DoD among the 8 patients from New York University (NYU).

Inspection of this figure reveals that 62.5% had a DoD between 0.42 years and 2.2 years. The median duration of hearing loss (time from onset of hearing loss to the time the degree of the
hearing loss becomes severe to profound), based on the patient’s subjective report as noted on the case history/intake form, was 9 years, with a range from 2 years to 28 years (see Figure 2).

Figure 2. Histogram of Duration of Hearing Loss (in years).

As can be seen from this figure, the duration of hearing loss was 2 to 10 years in 75% of the patients. Duration of hearing loss typically was longer than duration of deafness, as hearing loss often occurs progressively from the onset of NF2, and deafness often results after tumor treatment.

Of the 8 patients, 5 patients underwent surgical resection of the VS, 1 underwent gamma knife surgery (single dose), and 2 received conservative monitoring of the VS. (Notably, one patient had a unilateral VS on the contralateral ear that was monitored, and no VS on the
implanted ear.) All eight patients had full insertion of the electrode array and acceptable impedances on the active electrodes (see Table 1).
<table>
<thead>
<tr>
<th>Patient</th>
<th>Age at CI</th>
<th>Gender</th>
<th>VS surgery</th>
<th>Duration of HL (^1) (years)</th>
<th>DoD (years)</th>
<th>Drug treatment</th>
<th>Tinnitus</th>
<th>Implant</th>
<th>Processor</th>
<th>NRTS (^2) (≥1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65</td>
<td>F(^2)</td>
<td>Resection</td>
<td>29</td>
<td>20.5</td>
<td>No</td>
<td>No</td>
<td>Contour Adv.</td>
<td>N5 CP810</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>M(^3)</td>
<td>Resection</td>
<td>9</td>
<td>2.2</td>
<td>Yes (Avastin)</td>
<td>Yes</td>
<td>Nucleus 512</td>
<td>N5 CP810</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>F</td>
<td>Resection</td>
<td>5</td>
<td>0.42</td>
<td>No</td>
<td>Yes</td>
<td>Freedom CA</td>
<td>N6 CP910</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>56</td>
<td>M</td>
<td>Resection</td>
<td>13</td>
<td>10.8</td>
<td>No</td>
<td>NA(^2)</td>
<td>MScala 90k</td>
<td>Naida Q70</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>46</td>
<td>F</td>
<td>Monitoring</td>
<td>10</td>
<td>10</td>
<td>No</td>
<td>NA</td>
<td>Contour Adv.</td>
<td>N6 CP910</td>
<td>NA</td>
</tr>
<tr>
<td>6</td>
<td>53</td>
<td>F</td>
<td>Monitoring</td>
<td>4</td>
<td>2</td>
<td>No</td>
<td>Yes</td>
<td>CI24M</td>
<td>Sprint</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>54</td>
<td>M</td>
<td>Gamma Knife</td>
<td>9</td>
<td>2</td>
<td>No</td>
<td>Yes</td>
<td>Synchrony Flex</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>34</td>
<td>M</td>
<td>Resection</td>
<td>2</td>
<td>0.42</td>
<td>No</td>
<td>Yes</td>
<td>Nucleus 512</td>
<td>N5 CP810</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\(^1\)HL = Hearing loss

\(^2\)NRTS = Neural Response Thresholds

\(^2\)F = Female

\(^3\)M = Male

\(^4\)NA = Not applicable
### Table 2

*New York University Data Set: Pre-Cl Evaluation Characteristics*

<table>
<thead>
<tr>
<th>Patient</th>
<th>Aided PTA(^1) ipsi (dB)</th>
<th>Aided PTA contra (dB)</th>
<th>CNCw(^2) aided</th>
<th>CNCp(^3) aided</th>
<th>Sentence recognition score (in quiet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
<td>0%</td>
<td>15%</td>
<td>NA(^4)</td>
</tr>
<tr>
<td>2</td>
<td>89</td>
<td>85</td>
<td>0%</td>
<td>0%</td>
<td>0% AzBio</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>100</td>
<td>0%</td>
<td>0%</td>
<td>NA</td>
</tr>
<tr>
<td>4</td>
<td>46</td>
<td>36</td>
<td>8%</td>
<td>31%</td>
<td>4% AzBio</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>120</td>
<td>0%</td>
<td>0%</td>
<td>0% AzBio</td>
</tr>
<tr>
<td>6</td>
<td>97</td>
<td>120</td>
<td>0%</td>
<td>0%</td>
<td>0% HINT</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>45</td>
<td>18%</td>
<td>43%</td>
<td>42% AzBio</td>
</tr>
<tr>
<td>8</td>
<td>77.5</td>
<td>35</td>
<td>2%</td>
<td>12%</td>
<td>0% HINT</td>
</tr>
</tbody>
</table>

\(^1\)4 frequency pure tone averages (500, 1000, 2000, and 4000 Hz)

\(^2\)CNCw = CNC word score

\(^3\)CNCp = CNC phoneme score

\(^4\)NA = Not applicable
### Table 3

**New York University Data Set: Post-CI Results**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Length of follow-up (months)</th>
<th>Aided PTA(^1) ipsi (dB)</th>
<th>Open-set speech recognition</th>
<th>CNCw(^2) Aided</th>
<th>CNCp(^3) Aided</th>
<th>Sentence recognition score (in quiet)</th>
<th>Daily user</th>
<th>Performance level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>25</td>
<td>Yes</td>
<td>76%</td>
<td>NA(^4)</td>
<td>NA</td>
<td>Yes</td>
<td>HP(^5)</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>17.5</td>
<td>Yes</td>
<td>58%</td>
<td>79%</td>
<td>85% AzBio</td>
<td>Yes</td>
<td>HP</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>25</td>
<td>Yes</td>
<td>88%</td>
<td>NA</td>
<td>NA</td>
<td>Yes</td>
<td>HP</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>NA</td>
<td>Yes</td>
<td>10%</td>
<td>27%</td>
<td>50% HINT</td>
<td>Yes</td>
<td>IP</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>NA</td>
<td>Yes</td>
<td>60%</td>
<td>76%</td>
<td>77% AzBio</td>
<td>Yes</td>
<td>HP</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>37.5</td>
<td>Yes</td>
<td>44%</td>
<td>69%</td>
<td>91% HINT</td>
<td>Yes</td>
<td>HP</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>32.5</td>
<td>Yes</td>
<td>34%</td>
<td>64%</td>
<td>72% AzBio</td>
<td>Yes</td>
<td>HP</td>
</tr>
<tr>
<td>8</td>
<td>87</td>
<td>NA</td>
<td>No</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Yes</td>
<td>NA</td>
</tr>
</tbody>
</table>

\(^1\)4 frequency pure tone averages (500, 1000, 2000, and 4000 Hz)

\(^2\)CNCw = CNC word score

\(^3\)CNCp = CNC phoneme score

\(^4\)NA = Not applicable

\(^5\)HP = High performing
Median length of follow-up post cochlear implantation was 12 months, with a range of 3 to 120 months. The median CNC word-recognition score was 51%, with a range of 0 – 88%. Of the 8 patients, 6 had CNC phoneme scores; the median CNC phoneme score was 64%, with a range of 0 to 79%. Sentence testing using the Hearing in Noise test (in quiet) and the AZ Bio Sentence Test (in quiet), was conducted in 6 of the 8 patients; in these patients, the median score was 72%, with a range from 0 to 91%.

Of the eight patients, seven obtained open-set speech recognition post-implantation. All eight of the patients reported being daily users of the implant (see Table 2). Of the 8 patients, 6 were high performers, 1 was an intermediate performer, and 1 was a low performer. A scatterplot of CNC word scores in percent as function of duration of deafness in years is shown in Figure 3. Inspection of this scatterplot reveals no relation between these variables.
Figure 3. Scatterplot of CNC word score as a function of DoD Among NYU Patients

A scatterplot of CNC word scores in percent as a function of age at implantation in years (yrs) is shown in Figure 4.

Figure 4. Scatterplot of CNC word score as a function of age.

Inspection of this scatterplot reveals no relation between these variables. This finding is similar to data observed by Leung et al. (2005) for patients between 33 and 65 years of age; Leung et al., however, did not have patients who were more than 65 years of age. On the other hand, Mahmoud and Ruckenstein (2014) reported significantly higher AzBio and CNC scores in their group of patients who were more than 65 years of age than in their group of patients who were less than 65 years of age.
Of the 8 patients, 6 became high performers, 1 became an intermediate performer, and 1 failed to achieve open-set speech recognition. All eight patients, however, were daily users of the CI and reported obtaining benefit from use of the CI. Interestingly, the high performers included the two patients with conservative monitoring and the one patient who received gamma knife treatment for the tumor. Carlson et. al (2013) found that patients receiving stereotactic radio surgery trended towards better performance than those receiving surgical resection, although this difference did not reach statistical significance.

*Combined Data Set Based on 36 Patients (8 from New York University and 26 from Carlson et al., 2013)*

Mean age at implantation was 41.5 years, with a standard deviation of 14.7 years, and range of 15 to 67 years. It is unsurprising that the age of onset is higher in younger adults and adults not more than 65 years of age, than in adults more than 65 years of age, as the onset of NF2 usually is in the third and fourth decades of life. Gender distribution was similar, with 19 males and 17 females. The mean DoD was 4.0 years, with a standard deviation of 6.7 years, and range of 0.3 to 26 years. The majority of patients had a relatively short DoD not exceeding 2 years (see Figure 5).
Figure 5. Histogram of DoD Among Review Patients (in years)

A short DoD among many patients is likely because tumor treatment can cause an immediate or quick progression in hearing loss, leaving the individual to pursue an auditory rehabilitation options.

Mean length of follow-up for these patients was 40 months, with a standard deviation of 38.2 months, and a range of 2 to 120 months. The mean CNC word score was 34.0%, with a standard deviation of 31.3 percent, and a range from 0% to 88%. Some degree of open-set speech recognition, largely based on the AZBio or HINT in quiet, was achieved in 67% of the sample. The mean sentence-recognition score was 48.2%, with a standard deviation of 39.4% and a range from 0% to 98%.
A scatterplot of the CNC word score in percent as a function of duration of deafness is shown in Figure 6.

**Figure 6. Scatterplot of CNC word score as a function of DoD Among Review Patients**

Inspection of this scatterplot reveals the absence of a linear relation between these variables.

Inspection of this scatterplot also shows that the distribution of DoD appears to be skewed; the majority had a duration of deafness that was less than 2 years. Among the patients with a DoD that was greater than 2 years (N = 10), only 3 achieved CNC word-recognition scores greater than 20%. In comparison, among the 26 patients with a DoD not exceeding 2 years, 69% achieved CNC word scores exceeding 20% (see Table 4)
Table 4

Duration of Deafness (DoD) and High Performers (HP) versus Intermediate Performers (IP)

<table>
<thead>
<tr>
<th></th>
<th>Short DoD (≤ 2 years)</th>
<th>Long DoD &gt; 2 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of patients</td>
<td>26</td>
<td>10</td>
</tr>
<tr>
<td>Number of IP or HP</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>Percent (%) of IP or HP</td>
<td>69</td>
<td>30</td>
</tr>
</tbody>
</table>

Inspection of Table 4 reveals that the group with a shorter DoD has a greater chance of becoming intermediate or high performers than the group with a longer DoD. Nearly 70% of the patients with a shorter DoD had considerable speech understanding post cochlear implantation versus approximately 30% of the group with a longer DoD. But the difference was not statistically significant, probably because of the small sample size for the group with the longer DoD.

The scatterplot of CNC word score as a function of age at implantation fails to reveal a linear relation between these variables (see Figure 7).
Figure 7. Scatterplot of CNC word score as a function of age at implantation.

Holden et al. (2013) reported that when age at implantation exceeds 65 years, the relation between age at implantation and word-recognition score becomes inverse. The results of studies on this relation, however, are inconclusive (Budenz et al., 2011, Carlson et al., 2013, Friedland et al., 2010). The sample of patients in the present study (see Tables 5, 6, 7) was mostly under the age of 65 years, with only 3 patients over 65 years. Thus, unsurprisingly, no correlation was found between age at implantation and CNC word score in this study based on 36 patients.
### Table 5

**Review Data: Surgical Resection Patients**

<table>
<thead>
<tr>
<th>Study</th>
<th>Patient</th>
<th>Age at CI/Gender</th>
<th>DoD (years)</th>
<th>Length of follow-up (months)</th>
<th>Open-set speech recognition</th>
<th>Speech recognition score (CNCw/CNCp)¹</th>
<th>Sentence-recognition score in quiet</th>
<th>Performance level (HP/IP/LP)²</th>
<th>Daily CI user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present study</td>
<td>1</td>
<td>65/F³</td>
<td>20.5</td>
<td>12</td>
<td>Yes</td>
<td>76%</td>
<td>NA⁴</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>33/M⁵</td>
<td>2</td>
<td>3</td>
<td>Yes</td>
<td>58/79%</td>
<td>89% AzBio</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>38/F</td>
<td>0.4</td>
<td>120</td>
<td>Yes</td>
<td>88%</td>
<td>NA</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>56/M</td>
<td>10.8</td>
<td>3</td>
<td>Yes</td>
<td>10/27%</td>
<td>50% HINT</td>
<td>IP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>34/M</td>
<td>2</td>
<td>87</td>
<td>No</td>
<td>0%</td>
<td>NA</td>
<td>NA</td>
<td>Yes</td>
</tr>
<tr>
<td>Carlson et al.</td>
<td>1</td>
<td>67/M</td>
<td>0.3</td>
<td>60</td>
<td>Yes</td>
<td>22% w</td>
<td>32% AzBio</td>
<td>IP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>46/M</td>
<td>1</td>
<td>80</td>
<td>Yes</td>
<td>30%/58%</td>
<td>47% AzBio</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>65/F</td>
<td>26</td>
<td>47</td>
<td>No</td>
<td>0%</td>
<td>NA</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>25/F</td>
<td>0.3</td>
<td>38</td>
<td>No</td>
<td>0%</td>
<td>NA</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>55/M</td>
<td>21</td>
<td>32</td>
<td>No</td>
<td>0%</td>
<td>NA</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td>Roehm et al.</td>
<td>1</td>
<td>30/M</td>
<td>0.3</td>
<td>120</td>
<td>Yes</td>
<td>50/69 %</td>
<td>HINT 89%</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>22/M</td>
<td>11</td>
<td>12</td>
<td>No</td>
<td>0%</td>
<td>0%</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>27/M</td>
<td>0.5</td>
<td>2</td>
<td>No</td>
<td>0%</td>
<td>0%</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>38/F</td>
<td>1.4</td>
<td>15</td>
<td>Yes</td>
<td>80%</td>
<td>HP</td>
<td>IP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>19/F</td>
<td>3</td>
<td>16</td>
<td>No</td>
<td>0%</td>
<td>NR</td>
<td>IP</td>
<td>Yes</td>
</tr>
<tr>
<td>Vincenti et al.</td>
<td>1</td>
<td>47/F</td>
<td>0.3</td>
<td>12</td>
<td>Yes</td>
<td>80%</td>
<td>90%</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>24/F</td>
<td>0</td>
<td>12</td>
<td>Yes</td>
<td>72%</td>
<td>81%</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>32/M</td>
<td>0.3</td>
<td>12</td>
<td>Yes</td>
<td>50%</td>
<td>50%</td>
<td>IP</td>
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<tr>
<td></td>
<td>4</td>
<td>36/M</td>
<td>0.3</td>
<td>12</td>
<td>No</td>
<td>10%</td>
<td>0%</td>
<td>IP</td>
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<tr>
<td>Neff et al.</td>
<td>1</td>
<td>15/M</td>
<td>0.8</td>
<td>120</td>
<td>Yes</td>
<td>45%</td>
<td>*</td>
<td>HP</td>
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<td>Study</td>
<td>Patient</td>
<td>Age at CI/Gender</td>
<td>DoD (years)</td>
<td>Length of follow-up (months)</td>
<td>Open-set speech recognition</td>
<td>Speech recognition score (CNCw/CNCp)</td>
<td>Sentence-recognition score in quiet</td>
<td>Performance level (HP/IP/LP)</td>
<td>Daily CI user</td>
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<td>-------</td>
<td>---------</td>
<td>------------------</td>
<td>-------------</td>
<td>-----------------------------</td>
<td>----------------------------</td>
<td>-------------------------------------</td>
<td>-----------------------------------</td>
<td>-------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>3</td>
<td>59/F</td>
<td>6</td>
<td>60</td>
<td>Yes</td>
<td>*</td>
<td>96% HINT</td>
<td>HP</td>
<td>Yes</td>
<td></td>
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<tr>
<td>4</td>
<td>38/M</td>
<td>0.25</td>
<td>96</td>
<td>Yes</td>
<td>*</td>
<td>83% HINT</td>
<td>HP</td>
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<tr>
<td>5</td>
<td>37/F</td>
<td>0</td>
<td>60</td>
<td>Yes</td>
<td>*</td>
<td>96% HINT</td>
<td>HP</td>
<td>Yes</td>
<td></td>
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<tr>
<td>6</td>
<td>31/F</td>
<td>0.17</td>
<td>156</td>
<td>No</td>
<td>*</td>
<td>22% CID</td>
<td>No</td>
<td>Yes</td>
<td></td>
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<tr>
<td>Lustig et al.</td>
<td>1</td>
<td>35/M</td>
<td>0.42</td>
<td>28</td>
<td>No</td>
<td>0%</td>
<td>0%</td>
<td>*</td>
<td>Yes</td>
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<tr>
<td>2</td>
<td>51/M</td>
<td>0.42</td>
<td>40</td>
<td>Yes</td>
<td>79%</td>
<td>HP</td>
<td>Yes</td>
<td></td>
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<tr>
<td>3</td>
<td>16/M</td>
<td>1.08</td>
<td>30</td>
<td>No</td>
<td>0%</td>
<td>0%</td>
<td>*</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>28/F</td>
<td>0.33</td>
<td>88</td>
<td>No</td>
<td>0%</td>
<td>0%</td>
<td>*</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>57/F</td>
<td>8</td>
<td>9</td>
<td>Yes</td>
<td>12%/35%</td>
<td>HINT 98%</td>
<td>LP</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

1CNCw = CNC word score; CNCp = CNC phoneme score

2HP = high performing; IP = intermediate performing; LP = low performing

3F = Female

4NA = Not applicable

5M = Male
Table 6

Review Data: Stereotactic Radiosurgery Patients

<table>
<thead>
<tr>
<th>Study</th>
<th>Patient</th>
<th>Age at CI/Gender</th>
<th>DoD (years)</th>
<th>Length of follow-up (months)</th>
<th>Open-set speech recognition</th>
<th>Speech recognition score (CNCw/CNCp)¹</th>
<th>Sentence-recognition score in quiet</th>
<th>Performance level (HP/IP/LP)²</th>
<th>Daily CI user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Study</td>
<td>7</td>
<td>55/M³</td>
<td>2</td>
<td>6</td>
<td>Yes</td>
<td>34/64%</td>
<td>72% AzBio</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td>Carlson et al.</td>
<td>6</td>
<td>50/M</td>
<td>1.8</td>
<td>22</td>
<td>Yes</td>
<td>46/67%</td>
<td>95% HINT</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>61/M</td>
<td>1</td>
<td>56</td>
<td>Yes</td>
<td>86/93%</td>
<td>95% AzBio</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>44/F⁴</td>
<td>2</td>
<td>25</td>
<td>Yes</td>
<td>perception</td>
<td>perception</td>
<td>NA</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>37/M</td>
<td>14.8</td>
<td>12</td>
<td>No</td>
<td>NA³</td>
<td>NA</td>
<td>NA</td>
<td>No</td>
</tr>
<tr>
<td>Roehm et al.</td>
<td>4</td>
<td>60/F</td>
<td>1</td>
<td>36</td>
<td>Yes</td>
<td>68/87%</td>
<td>58% HINT</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td>Lustig et al.</td>
<td>4</td>
<td>41/F</td>
<td>3</td>
<td>17</td>
<td>Yes</td>
<td>46%</td>
<td>NA</td>
<td>LP</td>
<td>Yes</td>
</tr>
</tbody>
</table>

¹CNCw = CNC word score; CNCp = CNC phoneme score
²HP = high performing; IP = intermediate performing; LP = low performing
³M = Male
⁴F = Female
⁵NA = Not applicable
### Table 7

**Review Data: Conservative Monitoring Patients**

<table>
<thead>
<tr>
<th>Study</th>
<th>Patient</th>
<th>Age at CI/Gender</th>
<th>DoD (years)</th>
<th>Length of follow-up (months)</th>
<th>Open-set speech recognition</th>
<th>Speech recognition score (CNCw/CNCp)(^1)</th>
<th>Sentence-recognition score in quiet</th>
<th>Performance level (HP/IP/LP)(^2)</th>
<th>Daily CI user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present study</td>
<td>5</td>
<td>46/F(^3)</td>
<td>10</td>
<td>12</td>
<td>Yes</td>
<td>60/76%</td>
<td>77% AzBio</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>53/F</td>
<td>2</td>
<td>120</td>
<td>Yes</td>
<td>44/68%</td>
<td>72% AzBio</td>
<td>HP</td>
<td>Yes</td>
</tr>
<tr>
<td>Carlson et al.</td>
<td>10</td>
<td>32/F</td>
<td>0.58</td>
<td>97</td>
<td>Yes</td>
<td>28/51%</td>
<td>63% HINT</td>
<td>IP</td>
<td>Yes</td>
</tr>
<tr>
<td>Roehm et al.</td>
<td>3</td>
<td>53/F</td>
<td>0.92</td>
<td>24</td>
<td>Yes</td>
<td>34/53%</td>
<td>96% HINT</td>
<td>HP</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\(^1\)CNCw = CNC word score; CNCp = CNC phoneme score

\(^2\)HP = high performing; IP = intermediate performing; LP = low performing

\(^3\)F = Female
DISCUSSION

The objective of this study was to examine speech-perception outcomes among individuals with NF2, and also to determine if certain variables, such as DoD, age at implantation, etc., had significant effects on speech-perception scores. Of the 8 patients with NF2 and a CI examined from the New York University Cochlear Implant Center, 7 (88%) achieved open-set speech recognition and 8 were daily users of the implant. In the larger data set of 36 patients, 24 (67%) achieved open-set speech recognition and 33 patients (92%) reported being daily users of the implant.

For both the data set based on 8 patients and the larger data set based on 36 patients, no significant relation was observed between age at implantation and CNC word score or between DoD and word score. Of the 36 patients in the larger data set, 26 (about 72%) had a DoD not exceeding 2 years, suggesting that the distribution of DoD was skewed. Based on the larger data set, when speech-recognition performance for the group with short DoD (≤ 2 years) was compared with that for the group with longer DoD (> 2 years), the probability of achieving intermediate or high performance on speech-recognition testing was higher in the former than latter group. The results from the smaller and larger data sets align closely with the results of other research studies on NF2 and CI.

Limitations of this investigation included a small sample size for the data set based just on the patients who were implanted at New York University Medical Center and Cochlear Implant Center. The addition of these data to the patient data from Carlson et al.’s systematic review led to a larger sample size of 36 patients, which helped to overcome the limitation of a
small sample size. Despite this larger sample size, the sample lacked diversity on certain
variables. For example, DoD was short for most of patients. Among the 10 patients
(approximately 28%) with a DoD greater than 2 years, the DoD spanned a wide range from 3
to 26 years.

Also, most patients (N = 25) in the larger data underwent surgical resection of the VS
prior to CI surgery. Only 7 patients underwent radiation and only 4 underwent conservative
monitoring of the tumor. Future studies are needed to examine the effect of tumor treatment
(vestibular resection versus stereotactic radiation versus conservative monitoring) on speech-
recognition outcome. Carlson et al. (2013) found that those undergoing radiation therapy
trended towards better performance, but this result failed to reach statistical significance.

This study was retrospective in nature, and thus relied on the accuracy and availability
of data in patient charts and data reported on in other studies. The material employed for the
speech-recognition measure was variable among the patients; the only consistent measure
employed was the CNC word-recognition test. Future research should examine other speech-
recognition outcomes such as performance for phonemes and sentence-recognition materials.
For example, only 17 of the 36 patients had sentence-recognition scores available; sentence-
recognition scores help to further classify patients as high performers, intermediate
performers, or low performers.

Other independent variables not examined in this investigation that may influence
speech-recognition outcomes include tumor size, tumor location, and cochlear ossification.
Carlson et al. (2013) and Roehm et al. (2012) reported the effect of tumor size on speech-
recognition performance. Carlson et al. (2013) and Roehm et al. (2012) failed to find a significant relation between ipsilateral tumor size and speech-recognition performance with a CI. Limited research has been conducted on the effect of tumor size on speech-recognition outcome so further research is needed to examine the relation between these variables. Future research also is needed to examine the effect of tumor location (with respect to proximity to the cochlea) on speech-recognition outcome. Tumors in patients with NF2 tumors tend to develop in the cerebellopontine angle and grow from the Schwann cells of the vestibulocochlear nerve. Sometimes, however, the tumor can develop closer to the cochlea so further growth can damage the spiral ganglion cells or the cochlea itself.

In addition, cochlear ossification of the cochlea may be another independent variable to be considered. No patient in the smaller data set had cochlear ossification and every patient had a full-insertion of the electrode array. In the review data set of 36 patients, the effect of the variable of cochlear ossification was not reported since this data was not available from Carlson et al. (2013). Roehm et al. (2012) reported that two of the three patients who failed to develop open-set speech after cochlear implantation had cochlear ossification. Given the sparse data on the effects of cochlear ossification on speech-recognition outcome in patients with NF2 and CI, future research is needed on this topic.

The status of the auditory nerve is another important factor to consider. Electrical promontory stimulation is employed in patients with little to no residual hearing post tumor treatment to determine nerve function. It may be assumed that patients with better performance from a CI have a more intact auditory nerve than those who did not develop speech understanding. Lustig et al. (2006) proposed that for those patients who obtained good
speech-recognition performance after implantation, the probable etiology of hearing loss was vascular compromise to the cochlea rather than neuronal injury. Interestingly, those with radiation treatment trended towards better performance than those receiving surgical resection in this study and in previous research. Through histological studies of temporal bones, researchers have surmised that radiation affects the vascular endothelial cells supplying the tumor rather than the VS cells. Additionally, the cochlear artery, the main blood supply to the cochlea, often is vulnerable to the effects of radiation and other trauma. Radiation may damage the stria vascularis and outer hair cells (while leaving the spiral ganglion cells intact), thereby resulting in progressive hearing loss (Carlson et al., 2013).

Ossification of the cochlea is an important factor to consider when considering cochlear implantation in patients with NF2. Among the eight patients from NYU Medical Center, no cochlear ossification was reported and every patient had a full-insertion of the electrode array. In the larger data set of thirty-six patients, ossification was not a variable reported on in the 26 patients from the Carson et al. (2013) study. It appears likely that ossification would negatively affect performance outcomes. Roehm et al. (2012) reported that two of the three patients who did not develop open-set speech recognition post implantation had cochlear ossification. Additionally, these patients had a long time interval from VS resection to cochlear implantation.

Length of follow-up is another variable to consider when evaluating speech-recognition outcome in patients with NF2 and cochlear implantation. Length of follow-up in this study ranged from 3 to 120 months. With the complications among NF2 patients and the delayed effects of treatment, there has been concern of deterioration in performance. Carlson et al. (2013) reported that deterioration in performance occurred in 2 of 43 patients. One patient
who was implanted 20 years after undergoing high-dose radiation experienced a decline in performance at approximately one year after implant activation. The other patient who experienced decline in speech-recognition performance had undergone gamma knife treatment, CI placement, and then tumor growth necessitating surgical resection of the tumor and CI removal. Therefore, further longitudinal research is needed to determine long-term viability of CI in the NF2 population.

Although the number of individuals with NF2 is relatively small, the research findings may be illuminating for other patients with acoustic neuromas. The current candidacy guidelines for cochlear implantation in adults is bilateral moderate to profound hearing loss, with speech-recognition score less than 50% in the ear to be implanted, and no greater than 60% speech-recognition score in the opposite ear or binaurally. Nonetheless, the number of off-label cochlear implantations has been growing and recently includes patients with single-sided deafness and neural hearing loss. Acoustic neuromas account for 8% of all cranial lesions and often are unilateral. Treatment for an acoustic neuroma often results in sensorineural hearing loss. As candidacy for CI becomes more lenient, and as more patients with bilateral VS show benefit with a CI, a CI may become a standard rehabilitative option for non-NF2 patients with single-sided deafness or asymmetric hearing loss from an acoustic neuroma.

1 www.cochlear.com
CONCLUSIONS

In conclusion, cochlear implantation is a favorable option for individuals with NF2 who have an anatomically intact auditory nerve. Although speech perception after implantation is not guaranteed, those with a shorter DoD (less than 2 years) tend to achieve better open-set speech recognition than those with a longer DoD (at least 2 years). Also, patients with radiation therapy or conservative monitoring for a VS may do better with a CI because the auditory nerve tends to be intact after these procedures. Even if open-set speech recognition is not an outcome, it is very likely the patient will gain subjective benefit from the CI and wear it regularly. If a CI does not provide sufficient benefit for a patient, then an ABI still represents an option in management. Auditory rehabilitation in the NF2 population is difficult, and each patient presents unique challenges. If the auditory nerve can be preserved, even slightly, then a CI should be considered in these patients with NF2.
REFERENCES

New outcomes with auditory brainstem implants in NF2 patients. *Otology & Neurotology, 35*(10), 1844-1851.


