Correlation of Cochlear Nerve Size and Auditory Performance After Cochlear Implantation in Postlingually Deaf Patients

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Importance: Cochlear implantation (CI) yields outstanding results in postlingual deafness, but outcomes of auditory performance after CI are variable. Thus far, it has been difficult to accurately predict patient prognoses after CI.

Objective: To assess whether cochlear nerve (CN) size as measured with parasagittal magnetic resonance imaging (MRI) is correlated with auditory performance after CI in postlingually deaf patients.

Design: Retrospective study. All MRI results were reviewed by the same observer, who was blinded to the participants’ information.

Setting: A university tertiary care center.

Participants: All 102 postlingually deaf adults who underwent CI during the period August 2010 through June 2012 were eligible to participate. Thirty-four patients were excluded because MRI was not performed or was not of sufficient quality for assessment. Sixty-eight postlingually deaf adults (mean [range] age, 49 [16-77] years) were enrolled.

Exposure: Cochlear implantation.

Main Outcomes and Measures: Size of the CN and auditory performance.

Results: The mean (SD) cross-sectional area (CSA) of the CN was 0.922 (0.229) mm² and tended to decrease with age; however, there was no significant correlation between the size of the CN and age. The cause of deafness also did not affect the size of the CSA. However, CSA was negatively associated with both the duration of deafness ($P<.001$) and degree of hearing loss ($P=.008$ for the difference in CSA between ears with no more than 80-dB hearing loss [$n=25$] and ears with at least 101-dB hearing loss [$n=65$]). Interestingly, CSA was positively correlated with auditory performance after CI ($P=.04$).

Conclusions and Relevance: We suggest that measuring the size of the CN with parasagittal MRI can yield information that is helpful in preoperative counseling of patients.


Cochlear implantation (CI) is an effective modality for habilitation and has improved interventions for patients with sensorineural hearing loss. In particular, CI yields outstanding results in postlingual deafness.¹ However, outcomes of auditory performance after CI are variable. One known factor leading to this variability is believed to involve spiral ganglion cell survival and cochlear nerve (CN) function,² but it is difficult to accurately predict patient prognoses after CI by assessing the spiral ganglion and CN.

The development of magnetic resonance imaging (MRI) has enabled the production of high-resolution images. Parasagittal MRI is used to rule out CN deficiency. Studies were recently performed on the correlation between the CN and hearing loss and the correlation between the CN and age by measuring the size of the CN with MRI. Sildiroglu et al³ reported that 3-dimensional (3D) Fourier transformation constructive interference at steady-state (CISS) sequences yielded superior results in CN imaging and that acquired sensorineural hearing loss might not present with significant changes in CN size on MRI. In contrast, Russo et al⁴ reported that the size of the CN was mildly hypoplastic in children with profound sensorineural hearing loss. Kang et al⁵ suggested that the CN was unaffected by age in 3.0-T CISS imaging normalized to the facial nerve. Performance after CI is deter-
mined by various factors, including the degeneration of spiral ganglion cells and the CN. Therefore, the size of the CN may be a prognostic factor in CI outcome. However, whether the size of the CN on the basis of MRI is related to CI outcome is unknown.

The present study was conducted to assess the relationship between the size of the CN as determined by means of parasagittal MRI and multiple parameters in postlingually deaf patients and to determine whether the size of the CN is related to auditory performance after CI.

**METHODS**

**PARTICIPANTS**

During the period August 2010 through June 2012, 102 postlingually deaf adult patients with sensorineural hearing loss underwent CI at our institute. Thirty-four patients were excluded because MRI was not performed or was not of sufficient quality for assessment. Sixty-eight postlingually deaf adults (30 men and 38 women) with sensorineural hearing loss were enrolled. The mean (SD) age at the time of CI was 48.4 (16.5) years, and the mean (SD) duration of deafness was 22.8 (16.2) years. The inclusion criteria were onset of deafness after 4 years of age and implantation after 16 years of age. Hearing loss was evaluated on the basis of the mean pure tone audiogram result at 500, 1000, 2000, and 4000 Hz. The cause of deafness was investigated by means of medical record reviews, patient interviews, and blood sampling for genetic origin. This study was approved by the institutional review board of Severance Hospital, Yonsei University Health System, in Seoul, South Korea.

**MRI PROTOCOL AND MEASUREMENT OF CN SIZE**

The MRI scans were performed on a 3.0-T or 1.5-T MRI system (Intera Achieva; Philips Medical Systems) using a 6-channel sensitivity-encoding head coil. All images were evaluated with a parasagittal 3D-driven equilibrium sequence perpendicular to the internal auditory canal (IAC). The targeted parasagittal scan perpendicular to the long axis of the IAC was obtained with a T2-weighted 3D turbo spin-echo sequence with a driven equilibrium radio frequency reset pulse following routine MRI sequences with spin-echo T1-weighted and T2-weighted images. The imaging parameters for the 3D-driven equilibrium sequence were as follows: repetition time/echo time = 1500/200 milliseconds; 256 acquisition/256 reconstruction; 15-cm field of view; 1.5-mm section thickness; 0.75-mm overlap; number of acquisitions = 2; and acquisition time less than 5 minutes.

All MRI results were reviewed by the same observer, who was blinded to the participants’ information for consistency. The diameter of the CN was measured on the parasagittal image of the middle of the IAC using an automatic window-level setting. The parasagittal image through the IAC was selected as the middle of the IAC because the CN, facial nerve, and vestibular nerves could be optimally visualized (Figure 1). The vertical and horizontal diameters of the CN in the middle of the IAC were measured on the parasagittal images and used to calculate the cross-sectional area (CSA) of the CN: \[ \pi \left( \frac{\text{vertical diameter}}{2} \right) \left( \frac{\text{horizontal diameter}}{2} \right) \]. Measurements were obtained on parasagittal images using 0.01-mm electronic calipers provided with the Picture Archiving Communication System (Centricity; GE Healthcare).

**EVALUATION OF AUDITORY PERFORMANCE**

Evaluations of auditory performance were performed preoperatively and 3 months after CI. Sentence perception tests under auditory-only (AO) listening conditions without visual cues were performed using samples of words or sentences from everyday life in a noiseless sound-field environment. Auditory performance was assessed using a conventional test, the Korean version of the Central Institute for the Deaf test.6,7 The test was scored as the percentage of words repeated correctly. We used the postoperative AO sentence test scores as comparable indices.

**STATISTICAL ANALYSIS**

For statistical analysis, we used Microsoft Excel (Microsoft) and Origin software (OriginLab). Changes in CSA according to age, duration of deafness, and speech perception after CI were evaluated using simple linear regression analysis. Differences between groups were evaluated using 1-way analysis of variance. The Pearson correlation was used to assess the correlation between the CSA and each parameter. \( P < .05 \) was considered statistically significant.
RESULTS

We examined the correlation between the size of the CN and the patient’s age. The mean (SD) CN CSA was 0.922 (0.229) mm². **Figure 2A** shows a scatterplot of the CSA of the CN vs age. Linear regression analysis revealed a negative correlation between age and the CSA (slope = −0.00199). Pearson correlation coefficient, 0.143; \( P = .10 \). B. Correlation between the duration of deafness and the CSA of the cochlear nerve. Linear regression analysis showed a negative correlation between the duration of deafness and CSA (slope, −0.00724). Pearson correlation coefficient, −0.511; \( P < .001 \).

**Figure 2.** Scatterplots. A, Correlation between age and the cross-sectional area (CSA) of the cochlear nerve. Linear regression analysis showed a negative correlation between age and the CSA (slope = −0.00199). Pearson correlation coefficient, 0.143; \( P = .10 \). B, Correlation between the duration of deafness and the CSA of the cochlear nerve. Linear regression analysis showed a negative correlation between the duration of deafness and CSA (slope, −0.00724). Pearson correlation coefficient, −0.511; \( P < .001 \).

CN SIZE ACCORDING TO AGE

The duration of deafness ranged from 2 months to 61 years (median, 20 years). **Figure 2B** shows a scatterplot of the CSA vs the duration of deafness. Linear regression analysis showed a significant negative correlation between the CSA of the CN and the duration of deafness (\( P < .001 \)).

There might be interpersonal differences in CN size that are not related to the duration of deafness. Therefore, we also investigated the interaural difference in CN size of patients who have a gap of at least 9 years in the duration of deafness between the 2 ears. **Figure 3** shows the CSA in both ears. In all 5 patients, the CSA of the ear with the longer period of deafness was smaller than that of the ear with the shorter period of deafness. **Figure 4** shows parasagittal images of patient 2, who had been deaf in the right ear for 1 year and in the left ear for 10 years. The CN was smaller in the left ear with the longer duration of deafness.

CN SIZE ACCORDING TO HEARING LEVEL AND CAUSE OF DEAFNESS

We evaluated whether the size of the CN is related to hearing loss level or the cause of deafness. The patients’ ears were divided into 5 hearing loss groups: 70 or less, 71 to 80, 81 to 90, 91 to 100, and at least 101 dB (\( n = 7, 18, 22, 24, \) and 65, respectively). The CSA did not differ significantly among the 5 groups (\( P = .07 \)) (**Figure 5A**). Although not statistically significant, the CSA of the CN tended to decrease according to the level of hearing loss. The CSAs of the 80 or less dB (\( n = 25 \)) and the at least 101 dB (\( n = 65 \)) groups differed significantly (\( P = .008 \)).

The causes of deafness were classified as unknown, sudden sensorineural hearing loss, chronic otitis media, genetic origin, and other (\( n = 77, 29, 10, 18, \) and 2, respectively). The distribution of the causes of deafness is shown in **Figure 5B**. None of these causes of deafness had any significant differences in CSA (\( P = .86 \)).

CORRELATION BETWEEN CN SIZE AND AUDITORY PERFORMANCE AFTER CI

We examined the correlation between CN size and auditory performance before CI. **Figure 6A** shows a scatterplot of the CSA vs pre-CI AO sentence test scores. Linear regression analysis revealed a weak correlation between the CSA and AO sentence test scores that was not statistically significant (\( P = .15 \)). We also examined the correlation between CN size and the difference in AO (post-CI minus
pre-CI) sentence test scores, and linear regression analysis revealed a weak correlation (Figure 6B) \((P = .19)\). We examined the association between CN size and auditory performance after CI. Figure 6C shows a scatterplot of the CSA vs post-CI AO sentence test scores. Linear regression analysis revealed a significant positive correlation between the CSA and AO sentence test scores \((P = .04)\).

**DISCUSSION**

**CN SIZE ACCORDING TO AGE AND DURATION OF DEAFNESS**

Aging and hearing loss can lead to histological changes in the auditory system.\(^8\) In a mouse model of deafness, these histological changes manifest mainly in the organ of Corti or cochlear nucleus.\(^9\) Recent work in mice has shown a slow (months to years) loss of spiral ganglion cells and degeneration of the CN after noise exposure, even when there is no loss of hair cells.\(^{10}\) Deafness can also lead to changes in the CN. According to a human temporal bone study, the maximum diameters of the CN, vestibular nerves, and eighth cranial nerves were significantly smaller in the deaf population compared with normal-hearing controls.\(^{11}\) Recently, several studies attempted to show a correlation between the CN and hearing loss by means of high-resolution temporal bone computed tomography. These studies demonstrated that the length and width of the bony CN canal as measured by means of temporal bone computed tomography were significantly smaller in ears with congenital hearing loss.\(^{12,13}\)

There have been attempts to analyze CN size with MRI in various groups of patients with hearing loss. Sildiroglu et al\(^3\) measured CN size using 3D Fourier transformation CISS sequence images and found no significant changes in groups with acquired mild to moderate sensorineural hearing loss. In contrast, Russo et al\(^4\) reported that the size of the CN was hypoplastic in chil-
dren with profound congenital sensorineural hearing loss compared with normal controls. Herman and Angeli\textsuperscript{14} also suggested that parasagittal MRI could be used to measure the CN and that there was a significant difference in CSA between postlingually deafened and normally hearing adults.

We found that as the duration of deafness and level of hearing loss became more severe, the CSA of the CN decreased. That is, hearing loss can cause gradual degenerative changes in the CN, so the CN may be preserved at least for a time before it degenerates. Patient age did not significantly correlate with CN size in our study. Hinojosa and Nelson\textsuperscript{15} performed a human temporal bone study and showed that the number of spiral ganglion cells was related not only to age but also to hearing loss. Likewise, Kang et al\textsuperscript{5} reported that the CN was unaffected by age in normal-hearing ears.

**AUDITORY PERFORMANCE AND CN SIZE**

The factors affecting auditory performance after CI in postlingually deaf patients are variable. It has been suggested that the duration of deafness, age at implantation, duration of implant treatment, and etiology might affect performance.\textsuperscript{16} In a cadaveric human temporal bone study of patients who had undergone CI, residual hearing was correlated with both the number of spiral ganglion cells and auditory performance after CI.\textsuperscript{17} It was demonstrated that the diameters of the CN, vestibular nerves, and eighth cranial nerves were strongly correlated with the total spiral ganglion cell count.\textsuperscript{18} Therefore, the size of the CN is presumed to be associated with auditory performance after CI. The correlation of the CN with auditory performance after CI was mentioned in patients with congenital inner ear anomalies.\textsuperscript{19} In addition, it was previously reported that children with hypoplasia or aplasia of the CN showed poor auditory performance after CI.\textsuperscript{20,21}

We found that the size of the CN was correlated with post-CI AO sentence test scores. However, there was only a weak correlation between the AO (post-CI minus pre-CI) sentence test scores and the size of the CN, which was not statistically significant. We think that such a result stemmed from the weak tendency of the correlation between pre-CI AO sentence test scores and the size of the CN. The weak pre-CI correlation was augmented by CI, so that the post-CI AO sentence test score and the size of the CN were significantly correlated. Therefore, we found that the size of the CN measured with MRI was positively correlated with auditory performance after CI, and it may have potential value as a prognostic factor for the CI outcome.

In conclusion, to our knowledge, we are the first to report that the size of the CN as measured with MRI is correlated with performance after CI in postlingually deaf patients. Our present results suggest that MRI can be used to predict residual hearing and auditory performance after CI in patients with postlingual deafness. Because the hearing loss of the patients resulted from multiple causes, additional investigations are needed to analyze the correlation of the CN size with auditory performance in more homogeneous patient groups. However, our study suggests that measuring the size of the CN with parasagittal MRI may provide useful information for preoperative counseling of patients.

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**Figure 6.** Correlation between auditory-only (AO) sentence test scores and cross-sectional area (CSA). A, Pre-cochlear implantation (CI) test scores (slope, 0.00162). Pearson correlation coefficient, 0.155; \( P = .15 \). B, (Post-CI – Pre-CI) test scores (slope, 0.00096). Pearson correlation coefficient, 0.142; \( P = .19 \). C, Post-CI test scores (slope, 0.00131). Pearson correlation coefficient, 0.216; \( P = .04 \).
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