


INTRACOCHLEAR FACTORS CONTRIBUTING TO PSYCHOPHYSICAL PERCEPTS FOLLOWING COCHLEAR IMPLANTATION: A CASE STUDY

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INTRODUCTION

It is conceivable that the variations of performance of cochlear implant patients can be related to several factors. Shiroma et al. investigated which factors contributed to the speech recognition ability of cochlear implant patients; multiple regression analysis showed that postoperative psychophysical percepts such as threshold level (T level), maximum comfortable loudness level (C level), and dynamic ranges (DR) may play an important role in speech recognition ability. In this paper, we focus on determining which intracochlear factors contribute to these postoperative psychophysical percepts of the 22-channel cochlear implant system. We made a three-dimensional (3-D) computer reconstruction from the temporal bone of a cochlear implant patient and measured the following factors: distance between the electrode ring’s center and the Rosenthal’s canal center (dis); the cross-sectional areas of loose and dense fibrous tissue (flt, dft), their sum, fibrous tissue (ft), and new bone (nb) as inner ear pathologic changes; and the density of residual spiral ganglion cells (sgc). The interrelationship between the postoperative psychophysical percepts and these factors is analyzed and discussed.

CASE REPORT

The 74-year-old patient had a history of sensorineural hearing loss of unknown cause from childhood, and became totally deaf at age 68 (average hearing threshold: right, 101.3 dB; left, 103.7 dB). He was implanted in the left ear at age 71, and received significant benefit from the use of the multichannel implant. The patient died of heart failure 33 months after implantation. A glutaraldehyde-formalin solution was injected into the middle ear and around the implanted receiver-stimulator package within 6 hours postmortem, and the left temporal bone was removed within 24 hours. At this time, the electrode array was removed from the temporal bone.

TEMPORAL BONE AND PREPARATION OF IMAGES

The temporal bone was prepared for light microscopy by the standard methods of decalcification, celloidin embedding, horizontal serial sectioning at 30 µm, hematoxylin and eosin stain, and mounting on glass slides. There was some fibrous tissue and new bone along the electrode array (Fig 1).

Fig 1. Lower basal turn, showing full fibrous tissue and new bone in scala tympani. SM — scala media, E — electrode array tract,flt — loose fibrous tissue, nb — new bone.
A 3-D computer model was created from the 107 sections including the cochlea; every third section including Rosenthal's canal was used to count the number of spiral ganglion cells.

Input for the reconstruction can be any series of histologic slices. Temporal bone sections were viewed through a microscope, and a video camera (the Panasonic WV-CD20) was connected to the personal computer via a Data Translation DT2851 frame-grabber card. We marked and stored coordinates of the loose and dense fibrous tissue, new bone, the centerpoint of spiral ganglion cells, and the midpoint of the basilar membrane and the organ of Corti (OC). Borders of each feature could be outlined manually via the screen cursor or detected automatically with an algorithm based on gray levels. Single-point features such as the position of spiral ganglion cells and OCs were entered manually with the cursor. After all relevant points and borders of a given section had been stored, they could be displayed as a red overlay on the real-time image of the next serial section. Thus, the next section could be maneuvered until the best visual fit with all the borders of the previous section had been obtained. The 3-D reconstruction was made after all features obtained from sequential sections were sorted; the area plus perimeter calculations were added in the file, and the positions were confirmed by the plain film postoperative radiograph (Fig 2). This temporal bone was cut at an angle of 62° between the plane of section and the plane of radiograph. Total volumes were calculated as the sum of areas times section intervals (30 µm).

The position of the OC was used as the abscissa for mapping all data. A distance map of the OC was made by summing the distances between successive pairs of points, starting at the osteotomy site (as zero) and continuing to the apical end. The position of each electrode's ring was calculated by fitting the model to the radiograph. One program module can calculate the relative cross-sectional area (CSA) of features and the density of spiral ganglion cells. To find the CSA, each feature in each section is projected onto the display of the OC. The position of each endpoint, as found by the orthogonal projection, is noted. The contribution of each feature to the CSA is its volume (area times section interval) divided by the OC distance over which it is distributed. For the total CSA at a given OC point, the contributions of all features overlapping that point are summed. The sgcl was calculated similarly, with ganglion cell counts (measured by the Königsmark formula) used instead of volumes, and densities per millimeter instead of CSA. In this study, we calculated the average CSA of loose fibrous tissue, dense fibrous tissue, and new bone at 0.3- to 0.4-mm intervals centered around the point corresponding to each electrode ring's center. The dis was measured directly as a point-to-point distance. Three psychophysical percepts were assessed for the bipolar + 1 mode, so all the anatomic factors were calculated for the electrode ring in the middle of bipolar + 1 stimulation. Furthermore, the psychophysical percepts' values were converted from the relative numbers to milliamperes.
To correlate the psychophysical percepts with the anatomic factors, Pearson's correlation coefficients were calculated. Multiple regression analysis was also performed to find the combination of factors that contribute to the performance. In the multiple regression analysis, T and C levels and DR were used as dependent variables, and the anatomic factors as independent variables. Furthermore, the correlation among independent variables was taken into consideration.

**RESULTS**

**Values of Anatomical Factors.** The length of the OC was 32.96 mm, the electrode array was inserted in the cochlea 18.04 mm, and Rosenthal's canal center was 15.63 mm long. There was fibrous tissue and new bone along the electrode array; their total volumes were 12.12 and 2.00 mm$^3$, respectively, and the scala tympani was almost filled with them at the lower basal turn (Figs 1, 3, and 4). The electrode array tract was surrounded by dense fibrous tissue. Values for dis were between 1.23 to 2.47 mm and tended to be shorter toward the apex of the cochlea (higher number of electrodes). The total number of spiral ganglion cells was 5,591, and the average density at 1-mm intervals of OC was 172.6 cells per millimeter. The spiral ganglion cells tended to be clustered near electrodes 13 through 16 and 19 (Figs 3 and 4).

**Simple Correlation.** The correlation coefficients among T level, C level, and DR and all factors are shown in Table 1. There was a strong positive correlation between the T and C levels but no significant correlation between either level and DR. The T level showed higher correlations with dis, ft + nb, ft, lift, and nb. Similarly, there was a significant correlation between sgc and DR, and a moderately high negative correlation between sgc and DR. Among the anatomic factors, there were especially high positive correlation coefficients among ft + nb, ft, lift, dt, and nb.

**Multiple Regression.** The ft + nb was selected as an independent variable because of the high correlation coefficients among ft + nb, ft, lift, dt, and nb. Thus, dis, sgc, and ft + nb were used as independent variables. All standard regression coefficients ($R^2$) and multiple regression coefficients ($R$) are shown in Table 2. For the T level, a shorter dis and a smaller ft + nb contributed significantly to its reduction; its coefficient of determination ($R^2$) was quite high (.876). The same com-

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**Table 1. Results of Simple Correlation Analysis (Pearson’s Correlation Coefficients)**

<table>
<thead>
<tr>
<th></th>
<th>T level</th>
<th>C level</th>
<th>DR</th>
<th>dis</th>
<th>sgc</th>
<th>ft + nb</th>
<th>ft</th>
<th>lift</th>
<th>dt</th>
<th>nb</th>
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<td>.256*</td>
<td>1</td>
<td>1</td>
<td>.715*</td>
<td>-197</td>
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<td>.638*</td>
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<tr>
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<td>.448</td>
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<td>1</td>
<td>1</td>
<td>.638*</td>
<td>-.285</td>
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<td>.934*</td>
<td>.938*</td>
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<td>-.169</td>
<td>.409</td>
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<td>.938*</td>
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<td>ft(ft + dt)</td>
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<td>.741*</td>
<td>-174</td>
<td>1</td>
<td>.448</td>
<td>.505§</td>
<td>1</td>
<td>.938*</td>
<td>.805*</td>
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<tr>
<td>lift</td>
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<td>.624†</td>
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<td>.191</td>
<td>-.497§</td>
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</table>

* See text for abbreviations. *p < .001. †p < .01. §p < .05.
bination also contributed to reduction of the C level. But we may consider that these factors indirectly affected the C level through the T level, because of a strong positive correlation between the T and C levels. For the DR, a higher sgc contributed to an increase, and its $R^2$ was 0.404.

**DISCUSSION**

A lower T level with a wider DR was considered to be related to sensitivity and function of the inner ear and speech recognition ability.\(^1\) Hence, which cochlear factors contribute to these psychophysical percepts? Shepherd et al.\(^4\) observed significant reductions in electrical auditory brain stem response thresholds as the electrode array was moved from the outer wall toward the modiolus in acute animal experiments. Our result corroborates this, so we can say a closer position of the electrode array to the modiolus is a more efficient design for implantable electrodes. The more histopathologic changes are found in the cochlea, the higher are the electrical auditory brain stem response thresholds, and the number of spiral ganglion cells is lower.\(^5\) Our data corroborate this quite well. Marsh et al.\(^6\) investigated a human implanted temporal bone and reported that a marked reduction in spiral ganglion cell count was responsible for the elevated T level. Our study has just a weakly significant correlation between sgc and T level in the simple correlation test, and no significant result in multiple regression analysis. On the other hand, it is of particular interest that a higher density of spiral ganglion cells shows a wider DR. In this case, DR had increased during about 6 months of implantation. In other words, the DR may be narrow shortly after implantation, but it may increase if there are sufficient residual spiral ganglion cells. This could lead to an improvement in speech recognition ability.

**REFERENCES**


**EFFECTIVENESS OF DIFFERENT ELECTRICAL STIMULATION CONDITIONS IN PRESERVATION OF SPIRAL GANGLION CELLS FOLLOWING DEAFNESS**

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From the Kresge Hearing Research Institute, Department of Otolaryngology, University of Michigan, Ann Arbor, Michigan. This study was supported in part by program project 5 PO1 DC00274 from the National Institutes of Health [National Institute on Deafness and Other Communication Disorders]. This study was performed in accordance with the PHS Policy on Humane Care and Use of Laboratory Animals, the NIH Guide for the Care and Use of Laboratory Animals, and the Animal Welfare Act (7 U.S.C. et seq.); the animal use protocol was approved by the Institutional Animal Care and Use Committee (IACUC) of the University of Michigan.

**INTRODUCTION**

With the destruction of inner hair cells (IHCs) there is auditory nerve degeneration. Changes in peripheral elements (scar formation)\(^1\) and distal neural processes\(^4\) begin within hours after IHC loss. Degeneration of spiral ganglion cells (SGPs) after IHC loss follows a course of weeks to months in lower mammals, such as guinea pigs,\(^6\) but may extend to years in humans.\(^8\) The mechanisms that underlie these changes are not clear at this time, although a number of theories have been proposed to account for these degenerative changes,\(^12\) including loss of survival or growth factors, changes in the cytoarchitecture, and loss of activity in the auditory nerve fibers that occurs with denervation (IHC loss). In the last case, it is proposed that because of the elimination of spontaneous and evoked activity in the SGPs, the cell recognizes an unnatural state and processes begin that lead (with time) into a necrotic or apoptotic cell death cycle. At this time it is not clear what these processes might be or which cell death cycle is elicited. Nor is it clear that the loss of activity is the prime initiating agent, although this notion is supported by studies that demonstrate a reduction in SGP degeneration following IHC loss in the presence of chronic electrical stimulation, via a cochlear implant.\(^13-16\) A clear definition of the mechanisms that are involved in SGP cell death following IHC destruction is important, both to increase our understanding of neuronal cell death with deafferentation and from a very practical clinical concern. The data are strong that a greater survival of auditory nerve elements in the profoundly deaf is associated with improved performance with the cochlear implant.\(^13-16\) With greater speech recognition and understanding benefits in human studies,\(^17,18\) and with greater speech recognition and understanding benefits in animal psychophysical studies,\(^17,18\) if we understand the mechanisms involved and the factors that determine the effectiveness of electrical stimulation in preserving SGPs, we should be able...
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