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Preservation of Cells of the Organ of Corti and Innervating Dendritic Processes Following Cochlear Implantation in the Human: An Immunohistochemical Study

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Abstract

Hypothesis—This study evaluates the degree of preservation of hair cells, supporting cells, and innervating dendritic processes after cochlear implantation in the human using immunohistochemical methods.

Background—Surgical insertion of a cochlear implant electrode induces various pathologic changes within the cochlea including insertional trauma, foreign body response, inflammation, fibrosis, and neo-osteogenesis. These changes may result in loss of residual acoustic hearing, adversely affecting the use of hybrid implants, and may result in loss of putative precursor cells, limiting the success of future regenerative protocols.

Methods—Twenty-eight celloidin-embedded temporal bones from fourteen patients with bilateral severe to profound sensorineural hearing loss and unilateral cochlear implants were studied. Two sections including the modiolus or basal turn from each temporal bone were stained using anti-neurofilament, anti-myosin-VIIa, and anti-tubulin antibodies in both implanted and unimplanted ears.

Results

Inner and outer hair cells: Immunoreactivity was reduced throughout the implanted cochlea and in the unimplanted cochlea with the exception of the apical turn.

Dendritic processes in the osseous spiral lamina: Immunoreactivity was significantly less along the electrode of the implanted cochlea than in the other segments.

Inner and outer pillars, inner and outer spiral bundles, and Deiters' cells: Immunoreactivity was similar in the implanted and unimplanted cochleae.

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Conflicts of interest

The authors have no conflicts of interest to disclose.

Conclusions—Insertion of a cochlear implant electrode may significantly affect the inner and outer hair cells both along and apical to the electrode, and dendritic processes in the osseous spiral lamina along the electrode. There was less effect on pillar cells, Deiters' cells, and spiral bundles.

Keywords

Cochlear implant; Organ of Corti; Hair cell; Supporting cell; Dendritic process; Immunohistochemistry; Human

Introduction

Cochlear implantation is an effective and established procedure for rehabilitation of patients with profound sensorineural hearing loss. However, insertion of a cochlear implant electrode may induce two kinds of changes within the cochlea: immediate trauma to the osseous spiral lamina, basilar membrane, spiral ligament, stria vascularis, and lateral cochlear wall; and a host tissue response to both trauma and the presence of a foreign body consisting of inflammation, fibrosis and neo-osteogenesis (1–9). Histologic evidence of a foreign body reaction has been described in 75–96 % of human temporal bone specimens after cochlear implantation (5, 6). The cellular immunologic response included B and T lymphocytes, foreign body giant cells, and macrophages (7). Li et al. (8) and Kamakura and Nadol (9) have reported a significant correlation between the degree of insertional trauma and the volume of intracochlear new bone and fibrous tissue after cochlear implantation. Kamakura and Nadol (9) have reported a significant negative correlation between the volume of new bone and word recognition score. These traumatic, inflammatory, and immunologic changes may also result in loss of residual hair cells and supporting cells in the organ of Corti and innervating dendritic processes.

Previous studies have demonstrated survival of hair cells apical to the insertional length of a stimulating electrode array in the cat (10), and little damage to the spiral ganglion cells in Rosenthal's canal in the human (11). Coco et al. (10) concluded that chronic electrical stimulation of an electrode array located in the basal turn did not adversely affect residual hair cells apical to the electrode tip. There has been no systematic evaluation of the preservation or loss of hair cells, supporting cells, and peripheral sensory neurons of the organ of Corti after cochlear implantation in the human.

The objective of the current study was to evaluate whether hair cells, supporting cells, and peripheral neurons are preserved after cochlear implantation in the human, both along and apical to the electrode track in the implanted ear as compared to the contralateral unimplanted ear using semi-quantitative analysis by immunohistochemical methods to better delineate these cytological elements in these cases with sensorineural hearing loss and subsequent cochlear implantation.

Materials and Methods

Subjects

Fourteen human cases from the collection of the Otopathology Laboratory of the Massachusetts Eye and Ear Infirmary from patients who in life had bilateral severe to

profound sensorineural hearing loss and had undergone unilateral cochlear implantation using various electrode designs were evaluated. The clinical histories of Case 9 (12) and Case 14 (13) have already been reported. Case 14 had undergone hearing preservation cochlear implantation. The causes of deafness, age at onset of hearing loss and deafness, implant type and ear, age at implantation, duration of implantation, length of the cochlear duct, and length of the intracochlear electrode array in all fourteen cases are presented in Table 1. The current study was approved by the Institutional Review Board of the Massachusetts Eye and Ear Infirmary.

Histological techniques

All 28 temporal bones (14 implanted and 14 contralateral unimplanted) were fixed in 10% buffered formalin. After decalcification in ethylene diamine tetra-acetic acid (EDTA) the electrode arrays were removed. The specimens were dehydrated in alcohol, embedded in celloidin, and sectioned at a thickness of 20 μ m in a horizontal plane. Every tenth section was stained with hematoxylin and eosin, and mounted on a glass slide for subsequent reconstruction and study.

2-D reconstruction of the cochlea

The semi-serial sections of the temporal bones were reconstructed by conventional 2-D methods (14, 15). The most apical section of the cochlea containing the electrode tip in which there was histologic evidence, such as a fibrous sheath around the electrode (8, 9, 16), and the entry point (cochleostomy) of the electrode into the cochlea were determined. The electrode lengths within the cochlea were calculated using 2-D reconstructions.

Immunohistochemical methods

Immunohistochemical labelling of the inner and outer hair cells, inner and outer pillar cells, Deiters' cells, dendritic processes in the osseous spiral lamina, and the inner and outer spiral bundles was done in all 28 cochleae. On the implanted side, sections which passed through the electrode track and apical to the track and corresponding sections on the unimplanted side were selected for immunostaining. As shown in Figure 1, the two sections provided data on six or seven specimens through the cochlear duct (four in the basal turn, two in the middle turn, and one or none in the apical turn). In most temporal bone specimens, this provided three or four cross sections of the cochlea along the electrode track and three or four cross sections apical to it (Table 2).

The celloidin sections were mounted on gelatin subbed glass slides. Celloidin was removed with changes of a solution of sodium hydroxide and methanol followed by 100% methanol rinses (17). The tissue was rehydrated from 100 % methanol to 70 % methanol and then distilled water. The sections were rinsed in phosphate buffered saline (PBS) and incubated in 5 % normal horse serum and then incubated in primary antibodies overnight in a humid chamber at room temperature.

Hair cells—Immunostaining of the hair cells was accomplished using an antibody to myosin-VIIa (Proteus Biosciences Inc., Ramona, CA) at a dilution of 1:200. Myosin-VIIa is expressed in inner and outer hair cells throughout life (18).

Supporting cells—For the pillar cells and the Deiters' cells, an antibody to tubulin (19) (Sigma, St Louis, Missouri) was used at a dilution of 1:15,000. The tubulin antibody stained inner and outer pillar cells and Deiters' cells (19).

Dendritic processes—For the dendritic processes in the osseous spiral lamina and spiral bundles below inner and outer hair cells, an antibody to 200 kD neurofilament (Boehringer Mannheim, Mannheim, Germany) was used at a dilution of 1:15,000. The antibody stained dendritic processes in both the osseous spiral lamina and spiral bundles (19, 20).

After primary incubation, sections were rinsed in 3 washes of PBS. Secondary antibodies diluted 1:200 and appropriate for the host species of primaries were applied for one hour, and sections were then rinsed 3 times with PBS. Avidin-Biotin-horseradish peroxidase (standard ABC kit, Vector Labs, Burlingame, CA) was applied for one hour and rinsed in PBS. Colorization was accomplished with 0.01 % diaminobenzidine and 0.01 % hydrogen peroxide (H₂O₂) for 5 to 10 minutes, and the sections were then rinsed in PBS, dehydrated in graded alcohols, and cover slips were applied (17, 19). Representative photomicrographs of the sections stained by these three antibodies are shown in Figure 2.

Evaluation of immunostaining results

Immunoreactivity at each cross section and for eight elements of the cochlea (inner hair cells; outer hair cells; inner pillars; outer pillars; Deiters' cells; inner spiral bundles; outer spiral bundles; dendritic processes of spiral ganglion neurons in the osseous spiral lamina) was scored as "0" (immunonegative) and "1" (immunopositive) for each immunostain. For each element, the immunopositive scores were summed in each of four cochlear segments defined as follows: Segment A, the segment along the electrode in the implanted ear; Segment B, the segment apical to the electrode in the implanted ear; Segment A', the same segment as Segment A in the unimplanted ear; Segment B', the same segment as Segment B in the unimplanted ear (Figure 3). The % ratios of the immunopositive score to the number of cross sections in each segment were calculated as shown in Table 2A–D.

Segregating changes induced by cochlear implantation from those of preimplant deafness

In order to differentiate changes to each of the elements induced by cochlear implantation from changes induced by hearing loss before cochlear implantation, differences of the % ratios for Segment A and A' (Segment A' minus Segment A), and for B and B' (Segment B' minus Segment B) were calculated (Table 2E, F). It was assumed that the unimplanted cochlea would serve as a control for changes induced by a sensorineural hearing loss of a similar degree and similar etiology in both ears before cochlear implantation (21, 22).

Statistical analysis

All data in Table 2 and Figure 4 were displayed as mean $\pm$ SEM. The repeated measures one-way ANOVA or one-way ANOVA and Tukey's multiple comparison post hoc test were performed to investigate statistical relationships among the % ratio of the immunostaining scores, using GraphPad Prism version 7.02 (GraphPad Software, Inc., La Jolla, CA). $P < 0.05$ was considered significant.

Results

Clinical and histopathological variables (Table 1)

The clinical and histopathologic variables in all 14 cases are presented in Table 1. There were six females and eight males with a mean age at death of 82 years, ranging from 57 to 96 years. There were five Advanced Bionics electrodes (Sylmar, CA, USA) and nine Cochlear Nucleus electrodes (Cochlear Corp., Sydney, Australia). The mean duration of implantation was 136 months, ranging from 12 to 354 months. There were no re-implantation cases. The mean length of cochlear duct of the implanted ear and of the unimplanted ear were both 35 mm, ranging from 31 to 38 mm, and from 32 to 39 mm, respectively. The mean length of the intracochlear electrode was 19 mm, ranging from 4 to 25 mm.

Scores and statistical analysis of immunostaining (Table 2A–D, Figure 4A–H)

Inner and outer hair cells—The mean % ratio for Segment B' was significantly higher than those of the other three segments (A, A', B) (Figure 4A, B) (repeated measures one-way ANOVA: $P < 0.001$, both; Tukey's multiple comparison post hoc test: $P < 0.001$, or 0.01).

Supporting cells (inner and outer pillars, and Deiters' cells)—The mean % ratio for Segment A and A' were significantly lower than those of Segment B and B' (Figure 4C, D, E) (repeated measures one-way ANOVA: $P < 0.001$, each; Tukey's multiple comparison post hoc test: $P < 0.01$ or 0.05).

Dendritic processes—The mean % ratio for Segment A was significantly lower than those of the other three segments for the dendritic processes of spiral ganglion neurons in the osseous spiral lamina (Figure 4F) (repeated measures one-way ANOVA: $P < 0.001$; Tukey's multiple comparison post hoc test: $P < 0.001$, or 0.05). The mean % ratio for Segment A and A' were significantly lower than those of Segment B and B' for inner and outer spiral bundles (Figure 4G, H) (repeated measures one-way ANOVA: $P < 0.001$, each; Tukey's multiple comparison post hoc test: $P < 0.001$, 0.01, or 0.05).

Differences between Segment A and A', and B and B' (Table 2E, F, Figure 4I, J)

Differences of the % ratios of immunopositive score between Segment A and A' ($A' - A$), and B and B' ($B' - B$) are shown in Table 2E, F, and Figure 4I, J. For $A' - A$, the mean difference of the % ratios of immunopositive scores for dendritic processes in the osseous spiral lamina tended to be higher (one-way ANOVA: not significant). For $B' - B$, the mean differences of the % ratios of immunopositive scores for inner and outer hair cells were significantly higher than those for inner and outer pillars, Deiters' cells, and dendritic processes in the osseous spiral lamina (one-way ANOVA: $P < 0.001$; Tukey's multiple comparison post hoc test: $P < 0.05$, or 0.01).

Discussion

Preservation of cells of the organ of Corti and innervating dendritic processes

Previous studies have reported that intracochlear insertion of the implant electrode may cause traumatic, inflammatory, and cellular immunologic changes within the cochlea (1, 3–9), which may affect the survival of cytologic elements, especially hair cells, supporting cells, and innervating dendritic processes both along and apical to the electrode track within the cochlea. Additionally, patients who undergo cochlear implantation may have loss of cells of the organ of Corti and innervating dendritic processes before implantation. This may influence success of cochlear implants using combined acoustic and electrical stimulation or hypothetical future regenerative therapy of the inner ear for profound hearing loss. In the current study, both the inner and outer hair cells of Segment A, B, and A' were significantly less preserved than those of Segment B' (Figure 4A, B). This suggested that the inserted electrode adversely affected the survival of hair cells apical to the electrode track. However, unlike the results of the current study, Coco et al. (10) demonstrated approximately 60 % survival of the hair cells in the apical turn up to 252 days after cochlear implantation with chronic electrical stimulation for up to 1127 hours in eight partially deafened cats. This difference may be due to the difference in the duration of implantation between the current study (mean 136 months, ranging from 12 to 354 months) and the report by Coco et al. (10) (mean 209 days, ranging from 111 to 252 days). Long-term electrical stimulation may affect the hair cells apical to, as well as, along the stimulating electrode.

For the inner and outer pillars, Deiters' cells, and inner and outer spiral bundles, there were not significant differences between the % ratios of immunopositive scores for Segment A and A', and similarly between Segment B and B' (Figure 4C, D, E, G, H). This suggested that although the morphology of these elements was partially affected in some of the specimens, the insertion of the electrode may not significantly affect these elements. Immunohistochemical animal study by Eshraghi, et al. (23) revealed that molecular mechanisms of programmed cell death of the hair cells differ from those of the supporting cells. Eshraghi, et al. (24) also reported that programmed cell death initially starts in the supporting cells after electrode insertion trauma, followed by cell death of the hair cells. However, this was not clear in the current study maybe due to loss of hair cells and supporting cells before implantation had occurred. As to the dendritic processes between the spiral ganglion neurons and the organ of Corti in the osseous spiral lamina, degeneration was significantly more severe only along the electrode (Figure 4F). This suggested that only the dendritic processes in the osseous spiral lamina along the electrode track were likely to be negatively affected by the implanted electrode. Degeneration of the inner and outer spiral bundles was significantly (Segments B and B') or tended to be (Segment A') more severe in Segment A than the other three segments (Figure 4G, H). In most of 14 cases, the % ratios of immunopositive scores of the inner and outer spiral bundles were lower than that of the dendritic processes in the osseous spiral lamina in Segment A (Table 2A). The presence of the electrode or its electrical stimulation may adversely affect inner and outer spiral bundles, which may in turn induce retrograde degeneration of the dendritic processes of the cochlear nerve in the osseous spiral lamina. Although the fibers of the inner and outer spiral bundles are supplied by the same nerve found in the osseous spiral lamina, the statistical result of the

% ratios of immunopositive scores for dendritic processes in the osseous spiral lamina was different from those of inner and outer spiral bundles (Figure 4F, G, H). This may be due to lower mean % ratios of immunopositive scores for Segment A' for inner and outer spiral bundles than that of dendritic processes in the osseous spiral lamina, which suggests a retrograde degeneration of dendritic processes of the cochlear nerve due to severe to profound sensorineural hearing loss before implantation.

Effect of hearing loss before cochlear implantation

There was bilateral severe to profound sensorineural hearing loss in all 14 cases before cochlear implantation, resulting in loss of inner and outer hair cells and neurons before implantation. The mean % ratios of immunopositive scores both in the implanted and unimplanted ear may be influenced by hearing loss before implantation. In order to correct for losses caused by hearing loss before implantation, the implanted ear was compared with the unimplanted ear as a control. The mean % ratios of immunopositive scores for the elements of the organ of Corti (inner and outer hair cells, inner and outer pillars, Deiters' cells, and inner and outer spiral bundles) in Segment B' (apical turn) were significantly greater than those in Segment A' (basal turn) (Table 2A, B, Figure 4A–E, G, H). The most common pattern of loss of hair cells and supporting cells shows maximal damage in the basal turn with decreasing loss toward the apical turn, as is seen in presbycusis, some genetic deafness, severe or longstanding acoustic trauma, and some cases of idiopathic sudden sensorineural hearing loss (25). The results of the current study reflect similar patterns of cell loss and causes of deafness (Table 1). In Segment A and A', the differences for inner and outer hair cells, inner and outer spiral bundles, and dendritic processes in the osseous spiral lamina tended to be greater than the other three elements, but did not reach statistical significance (Figure 4I). This may be because the mean % ratios in Segment A and A' except that of dendritic processes in the osseous spiral lamina were low due to the effect of hearing loss before implantation (Table 2A, C). Along the electrode, insertion of the electrode and its electrical stimulation may adversely affect inner and outer hair cells and inner and outer spiral bundles as well as dendritic processes in the osseous spiral lamina. On the other hand, in Segment B and B', the differences for inner and outer hair cells were significantly higher than those of inner and outer pillars, Deiters' cells, and dendritic processes in the osseous spiral lamina (Figure 4J). This suggests that apical to the electrode, insertion of the electrode and its electrical stimulation may adversely affect hair cells with little effect on supporting cells and dendritic processes in the osseous spiral lamina.

Possibility of future regeneration therapy for the implanted cochlea

Regeneration of the inner ear is now being actively investigated. There is evidence that some of the supporting cells of the organ of Corti may serve as latent stem cells or progenitor cells which may be used in transdifferentiation (phenotypic conversion) of supporting cells into new hair cells, or alternately induction of supporting cells which re-enter the cell cycle to create new supporting cells and hair cells (26–36). The current study demonstrated that preservation of the inner and outer pillar cells and Deiters cells, possible candidates for hair cell regeneration, was similar in the implanted and unimplanted ear (Figure 4C, D, E), and therefore it may be possible to induce regeneration of hair cells particularly apical to the electrode track in the implanted as well as in unimplanted ears in the future.

Possibility of future combined stimulation of the implanted ear

In recent years, combining residual acoustic hearing and electric stimulation has been successful as a new strategy for those individuals who have profound high-frequency hearing loss at frequencies greater than 1500 Hz and less than 60 % discrimination scores (37). The benefits of combined electric and acoustic hearing in the same ear include better hearing in background noise and in quiet, and better spatial localization (13, 37–39). However, the current study demonstrated that hair cells were significantly affected not only along the electrode but also apical to it. In order to achieve successful combined stimulation, preservation of the hair cells is essential at least in the apical turn. In the current study, inner and/or outer hair cells were partially preserved in Segment B (apical to the electrode in the implanted ear) in 7 of 14 cases including Case 14 (with combined stimulation). Supporting cells including the pillar cells and Dieters' cells tended to be well-preserved apical to the electrode in the implanted as well as unimplanted ear in the current study. O'Leary et al. (40) demonstrated that poorer residual hearing after implantation correlated with a more extensive tissue response, lower outer hair cells counts, and injury of the osseous spiral lamina in the basal turn in the guinea pig. Quesnel et al. (13) have reported that decreased compliance at the round window and increased damping in the scala tympani due to intracochlear tissue response may be a possible cause of delayed hearing loss after hearing preservation cochlear implantation in the human.

Conclusions

Results of the current study suggested that insertion of a cochlear implant electrode may significantly negatively affect inner and outer hair cells both along and apical to the electrode, and dendritic processes in the osseous spiral lamina along the electrode. There were no significant differences in the pillar cells, Dieters' cells, and spiral bundles in the same segments between implanted and unimplanted ears. The differences of the % ratios of immunopositive scores between dendritic processes in the osseous spiral lamina and inner and outer spiral bundles may be due to retrograde degeneration of the dendritic processes of the cochlear nerve after cochlear implantation.

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Figure 1.

Two-dimensional reconstruction of both cochleae in Case 1.

The track of the cochlear implant electrode is shown in blue. The horizontal red lines indicate sections which were selected for immunostaining. A total of seven specimens of the cochlear duct were obtained, four along the cochlear implant track and three apical to the track.

Figure 2.

Representative photomicrographs of the sections stained by three antibodies.

A: Anti-myosin-VIIa immunostaining of the implanted cochlea in Case 12. The organ of Corti was seen in the middle and apical turns (OC). The electrode track (ET) was seen in the basal turn.

A': Higher magnification of the boxed area seen in A. No hair cells were stained.

B: Anti-myosin-VIIa immunostaining of the unimplanted cochlea in Case 12. The organ of Corti was seen in the middle and apical turns (OC).

B': Higher magnification of the boxed area seen in B. The inner (IHC) and outer hair cells (OHCs) were stained.

C: Anti-myosin-VIIa immunostaining of the implanted cochlea in Case 11. The organ of Corti was seen in the middle and apical turns (OC). The electrode track (ET) was seen in the lower basal turn.

C': Higher magnification of the boxed area seen in C. No hair cells were stained.

D: Anti-myosin-VIIa immunostaining of the unimplanted cochlea in Case 11. The organ of Corti was seen in the upper basal, middle and apical turns (OC).

D': Higher magnification of the boxed area seen in D. Only the inner (IHC) hair cell was stained.

E: Anti-tubulin immunostaining of the implanted cochlea in Case 3. The organ of Corti was seen in all turns (OC). The electrode track (ET) was seen in the basal turn.

E': Higher magnification of the boxed area seen in E. Phalangeal processes of Deiters' cells (Dp), inner (IP) and outer pillars (OP) were stained.

F: Anti-tubulin immunostaining of the unimplanted cochlea in Case 3. The organ of Corti was seen in all turns (OC).

F': Higher magnification of the boxed area seen in F. Phalangeal processes of Deiters' cells (Dp), inner (IP) and outer pillars (OP) were stained.

G: Anti-tubulin immunostaining of the implanted cochlea in Case 4. The organ of Corti was seen in all turns (OC). The electrode track (ET) was seen in the lower basal turn.

G': Higher magnification of the boxed area seen in G. Phalangeal processes (Dp) and cell body (Dc) of Deiters' cells, inner (IP) and outer pillars (OP) were stained.

H: Anti-tubulin immunostaining of the unimplanted cochlea in Case 4. The organ of Corti was seen in all turns (OC).

H': Higher magnification of the boxed area seen in H. Phalangeal processes of Deiters' cells (Dp), inner (IP) and outer pillars (OP) were stained.

I: Anti-neurofilament immunostaining of the implanted cochlea in Case 13. The electrode track (ET) was seen in the basal turn. Dendritic processes of spiral ganglion neurons in the osseous spiral lamina (OSL) were stained in all turns.

I': Higher magnification of the boxed area seen in I. Inner (ISB) and outer spiral bundles (OSBs) below the inner and outer hair cells were stained.

J: Anti-neurofilament immunostaining of the unimplanted cochlea in Case 13. Dendritic processes of spiral ganglion neurons in the osseous spiral lamina (OSL) were stained in all turns.

J': Higher magnification of the boxed area seen in J. Inner (ISB) and outer spiral bundles (OSBs) below the inner and outer hair cells were stained.

K: Anti-neurofilament immunostaining of the implanted cochlea in Case 8. The electrode track (ET) was seen in the lower basal turn. Dendritic processes of spiral ganglion neurons in the osseous spiral lamina (OSL) were stained in the upper basal, middle, and apical turns.

K': Higher magnification of the boxed area seen in K. Inner (ISB) and outer spiral bundles (OSBs) below the inner and outer hair cells were stained.

L: Anti-neurofilament immunostaining of the unimplanted cochlea in Case 8. Dendritic processes of spiral ganglion neurons in the osseous spiral lamina (OSL) were stained in all turns.

L': Higher magnification of the boxed area seen in L. Inner (ISB) and outer spiral bundles (OSBs) below the inner and outer hair cells were stained.

Figure 3.

Definition of the four segments in the implanted and unimplanted cochlea. Segment A was defined as that segment along the electrode track in the implanted cochlea. Segment B was defined as that segment apical to the electrode in the implanted cochlea. Segment A' was defined as the corresponding segment to Segment A in the unimplanted cochlea. Segment B' was defined as the corresponding segment to Segment B in the unimplanted cochlea.

Figure 4.

A–H, statistical analysis of the % ratios of immunostaining scores for the eight elements of the cochlea (Repeated measures one-way ANOVA and Tukey's multiple comparison post hoc test).

I, statistical analysis of the differences of the % ratios of immunostaining scores between Segment A and A' for the eight elements (One-way ANOVA and Tukey's multiple comparison post hoc test).

J, statistical analysis of the differences of the % ratios of immunostaining scores between Segment B and B' for the eight elements (One-way ANOVA and Tukey's multiple comparison post hoc test).

IHC indicates inner hair cells; OHC, outer hair cells; IP, inner pillars; OP, outer pillars; Deiters', Deiters' cells; OSL, dendritic processes in the osseous spiral lamina; ISB, inner spiral bundles; OSB, outer spiral bundles.

Table 1

Clinical and histopathologic demographics of the 14 cases studied.

Case	Age/Sex	Otologic disease	Age at onset of hearing loss (years)	Age at onset of deafness (years)	Cochlear implant	Implanted ear	Age at implant (years)	Duration of implantation (months)	Length of cochlear duct (Implanted/unimplanted) (mm)	Length of intracochlear electrode (mm)
1	84/F	Presbycusis	63	71	Nucleus 22	AD	72	151	33/32	18
2	76/M	Scarlet fever (suspected)	10	45	Nucleus 22	AS	59	204	31/32	16
3	89/M	Genetic (suspected)/Noise exposure	25	85	Advanced Bionics Hi-Res 90K Helix	AD	86	33	38/39	21
4	57/M	Superficial siderosis	36	51	Nucleus 24	AD	51	80	32/32	15
5	78/M	Noise exposure (suspected)	40	74	Nucleus 24 R	AS	74	83	38/39	25
6	83/M	Otosclerosis	16	52	Nucleus 22	AS	60	276	38/36	17
7	89/F	Genetic (suspected)	30	72	Nucleus 24 contour	AS	79	127	37/38	21
8	82/F	Chronic otitis media/ISSNHL	36	72	Advanced Bionics CII	AS	74	102	33/33	18
9	89/F	DFNA 5	38	66	Advanced Bionics Claron standard electrode	AS	70	230	36/37	22
10	96/M	Genetic (suspected)	50	90	Nucleus Freedom	AD	91	61	35/37	22
11	81/F	ISSNHL	29	29	Nucleus 22	AD	60	354	33/34	14
12	93/F	Unknown	53	82	Advanced Bionics Hi-Res 90K	AS	85	110	35/35	24
13	81/M	Noise exposure (suspected)	58	73	Advanced Bionics Hi-Res Advance 1J	AD	80	12	35/35	23
14	70/M	Noise exposure	30	63	Nucleus Hybrid S8	AS	63	75	34/33	4
Average	82		37	66			72	136	35/35	19

AS indicates left; AD, right; F, female; M, male; ISSNHL, idiopathic sudden sensorineural hearing loss.

Table 2

A–D, the % ratios of immunostaining scores to the numbers of cross sections in each segment for the eight elements of the cochlea.
E, the differences of the % ratios of immunostaining scores between Segment A and A ’ for the eight elements.
F, the differences of the % ratios of immunostaining scores between Segment B and B’ for the eight elements.

A	B																		
Segment A										Segment B									
Case	Number of cross sections	Elements of the cochlea								Case	Number of cross sections	Elements of the cochlea							
		IHC	OHC	IP	OP	Deiters'	OSL	ISB	OSB			IHC	OHC	IP	OP	Deiters'	OSL	ISB	OSB
1	4	0	0	0	0	0	50	0	0	1	3	0	33	33	100	100	67	33	
2	4	0	0	0	0	0	0	0	0	2	3	0	33	67	67	67	0	33	
3	4	0	0	75	75	50	75	25	0	3	3	0	0	100	100	100	67	100	
4	3	0	0	100	100	100	67	0	0	4	4	50	25	100	100	75	25	75	
5	4	0	25	25	25	50	50	0	0	5	3	0	33	100	100	100	100	100	
6	3	0	0	67	33	33	67	33	33	6	4	25	25	100	100	100	75	25	
7	4	0	25	25	25	25	50	0	0	7	3	0	0	67	67	100	67	67	
8	3	0	0	67	67	67	67	0	0	8	3	0	0	100	100	100	100	67	
9	4	0	0	0	0	0	50	0	0	9	3	0	0	0	0	100	33	33	
10	4	0	0	0	0	25	75	0	25	10	3	0	0	100	100	67	33	67	
11	3	0	0	0	0	0	33	0	0	11	4	25	0	75	75	50	75	0	
12	5	0	0	40	40	40	60	20	20	12	2	0	0	50	100	100	100	100	
13	5	0	0	100	100	100	100	80	40	13	2	0	0	100	100	100	100	100	
14	2	0	0	0	0	0	100	0	0	14	5	0	40	60	20	60	60	60	
Mean ± SEM		0	3.6 ± 2.4	35.6 ± 10.4	33.2 ± 10.1	35.0 ± 9.5	60.3 ± 6.8	11.3 ± 6.1	8.4 ± 3.9	Mean ± SEM		7.1 ± 4.1	13.5 ± 4.4	75.1 ± 8.4	75.9 ± 9.2	77.6 ± 7.8	96.2 ± 2.7	64.4 ± 8.5	61.4 ± 8.7
C	D																		
Segment A'										Segment B'									
Case	Number of cross sections	Elements of the cochlea								Case	Number of cross sections	Elements of the cochlea							
		IHC	OHC	IP	OP	Deiters'	OSL	ISB	OSB			IHC	OHC	IP	OP	Deiters'	OSL	ISB	OSB

C										D									
Segment A'										Segment B'									
Case	Number of cross sections	Elements of the cochlea								Case	Number of cross sections	Elements of the cochlea							
		IHC	OHC	IP	OP	Deiters'	OSL	ISB	OSB			IHC	OHC	IP	OP	Deiters'	OSL	ISB	OSB
2	3	0	0	0	0	0	100	0	0	2	4	50	25	25	25	25	100	50	50
3	4	0	25	100	100	100	100	75	75	3	3	33	67	100	100	100	100	100	100
4	3	0	0	67	67	67	33	0	0	4	4	50	50	100	100	100	75	0	50
5	4	0	25	50	25	50	100	0	25	5	3	33	67	100	100	100	100	100	100
6	4	25	25	100	100	100	50	50	50	6	3	67	67	100	100	100	100	100	100
7	4	0	0	0	0	25	100	0	0	7	3	67	67	100	100	100	100	100	100
8	3	33	100	100	100	100	100	100	100	8	3	0	100	100	100	100	100	100	100
9	4	0	0	0	0	0	100	0	0	9	3	0	0	0	0	0	100	33	33
10	4	0	0	50	50	50	100	25	25	10	3	0	33	100	100	100	100	100	100
11	3	0	0	0	0	0	67	0	0	11	4	75	25	100	100	100	100	100	100
12	5	20	0	20	0	20	100	20	0	12	2	50	50	100	100	100	100	100	100
13	5	100	100	100	100	100	100	100	100	13	2	100	100	100	100	100	100	100	100
14	2	0	0	0	0	0	100	0	0	14	5	60	80	20	0	80	100	80	60
Mean ± SEM		12.7 ± 7.4	19.6 ± 9.5	41.9 ± 11.8	38.7 ± 12.1	43.7 ± 11.4	89.3 ± 6.0	26.4 ± 10.3	26.8 ± 10.3	Mean ± SEM		44.1 ± 8.0	57.0 ± 7.7	79.4 ± 9.7	78.0 ± 10.5	83.7 ± 8.6	98.2 ± 1.8	80.7 ± 8.5	82.9 ± 6.7

Segment A' - Segment A										Segment B' - Segment B										F
Case	Elements of the cochlea								Case	Elements of the cochlea								OSB		
	IHC	OHC	IP	OP	Deiters'	OSL	ISB	OSB		IHC	OHC	IP	OP	Deiters'	OSL	ISB	OSB			
1	0	0	0	0	0	50	0	0	1	33	33	33	33	−33	0	0	33			
2	0	0	0	0	0	100	0	0	2	50	−8	−42	−42	−42	33	50	17			
3	0	25	25	25	50	25	50	75	3	33	67	0	0	0	0	33	0			
4	0	0	−33	−33	−33	−33	0	0	4	0	25	0	0	25	−25	−25	−25			
5	0	0	25	0	0	50	0	25	5	33	33	0	0	0	0	0	0			
6	25	25	33	67	67	−17	17	17	6	42	42	0	0	0	0	25	75			
7	0	−25	−25	−25	0	50	0	0	7	67	67	33	33	33	0	33	33			
8	33	100	33	33	33	33	100	100	8	0	100	0	0	0	0	0	33			

Segment A' - Segment A										Segment B' - Segment B										F
Case	Elements of the cochlea									Case	Elements of the cochlea									
	IHC	OHC	IP	OP	Deiters'	OSL	ISB	OSB	IHC		OHC	IP	OP	Deiters'	OSL	ISB	OSB			
9	0	0	0	0	0	50	0	0	0	9	0	0	0	0	0	0	0			
10	0	0	50	50	25	25	25	0	0	10	0	33	0	33	0	67	33			
11	0	0	0	0	0	33	0	0	50	11	50	25	25	50	0	25	100			
12	20	0	-20	-40	-20	40	0	-20	50	12	50	50	50	0	0	0	0			
13	100	100	0	0	0	0	20	60	100	13	100	100	0	0	0	0	0			
14	0	0	0	0	0	0	0	0	60	14	60	40	-40	20	20	20	0			
Mean ± SEM	12.7 ± 7.4	16.1 ± 10.0	6.3 ± 6.4	5.5 ± 8.0	8.7 ± 7.1	29.0 ± 9.0	15.1 ± 7.6	18.4 ± 9.3	37.0 ± 7.9	Mean ± SEM	37.0 ± 7.9	43.4 ± 8.5	4.2 ± 6.8	2.1 ± 5.2	6.1 ± 6.6	2.0 ± 3.4	16.3 ± 6.5	21.4 ± 8.9		

IHC indicates inner hair cells; OHC, outer hair cells; IP, inner pillars; OP, outer pillars; Deiters', Deiters' cells; OSL, dendritic processes in the osseous spiral lamina; ISB, inner spiral bundles; OSB, outer spiral bundles.