Otopathologic Changes in the Cochlea following Head Injury without Temporal Bone Fracture

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Abstract

Objective. Hearing loss following temporal bone (TB) fracture may result from direct transection of the middle and inner ear. The pathophysiology of hearing loss due to head injury without TB fracture, however, is not well understood. Few reports describe otopathologic findings. Herein, we investigate the pathologic findings of patients who sustained a head injury without evidence of a TB fracture.

Study Design. Otopathology study.

Setting. Otopathology laboratory.

Subjects. Subjects with a history of head injury without TB fracture.

Methods. The TBs of patients with head injury were evaluated by light microscopy. Inner ear anatomy was evaluated, including counts of spiral ganglion cells (SGCs), hair cells, pillar cells, atrophy of the stria vascularis, and the presence of endolymphatic hydrops. SGC counts were compared with those of historical age-matched controls.

Results. All cases (N = 6 TBs) had evidence of inner ear pathology. Of the 6 cases, 2 (33%) had severe loss of hair cells in all 3 turns of the cochlea, and 4 (67%) cases demonstrated moderate to severe loss at the basal turn of the cochlea. Four cases had scattered atrophy of the stria vascularis, and 3 (50%) had cochlear hydrops. The number of total SGCs was decreased, with an average 53% loss (range, 25%-79%) as compared with controls. The SGC count loss was evenly distributed along Rosenthal’s canal.

Conclusions. Patients with a history of head injury without TB fracture demonstrate inner ear pathology. Further studies are necessary to determine if otopathology findings are directly attributable to trauma.

Keywords

traumatic brain injury, hearing loss, sensorineural hearing loss, conductive hearing loss, inner ear, spiral ganglion cells, hair cells, temporal bone, histopathology

Received November 7, 2017; revised February 5, 2018; accepted March 20, 2018.

Head injury is a major worldwide cause of death and disability.1 In the United States, around 2.5 million Americans sustain head injury every year, resulting in nearly 50,000 deaths, 235,000 hospitalizations, and 2.8 million visits to the emergency room.2 Following injury, up to 90,000 individuals experience permanent disability, such as short- or long-term memory loss, cognition issues, neurobehavioral disability, and motor dysfunction.3,4

The prevalence of hearing loss following head injury is estimated to range from 14% to 67%.5-9 Head injuries may be classified as those with and without temporal bone (TB) fracture. In cases of head injury with a TB fracture, hearing loss is typically thought to be caused by direct anatomic disruption of the middle or inner ear sensory neuroepithelium or auditory nerve.10-12 Radiographic classification of the fracture location has been demonstrated to provide prognostic information regarding type of hearing loss, facial nerve function, as well as risk for cerebrospinal fluid leak and vascular injury.13-16

While hearing loss in the setting of head trauma with concurrent TB fracture is generally well studied, less is known about the pathophysiology of hearing loss due to head injury without TB fracture.17,18 In the absence of a TB
fracture, it can be difficult to predict whether a patient will sustain hearing loss after head injury. The terms “labyrinthine concussion,”19-21 “inner ear concussion,”22-24 “com- tion labyrinthitis,”20,25 and “otitis interna vasomoria”23 have been used in the literature since the era of Politzer,26 and are generally defined as head trauma resulting in sensorineural hearing loss without evidence of labyrinthine fracture. Reports of pathology of inner ear concussions, however, are sparse, and this term appears to be a nonspecific catchall phrase for hearing loss following head injury without TB fracture.

Taken together, while hearing loss secondary to head injury without TB fracture is a recognized clinical phenomenon, the precise pathophysiology remains unknown. Herein, we aim to evaluate the cochleae of patients who sustained head trauma without TB fracture to better understand associated histopathology that may give rise to auditory dysfunction.

Method

Subjects

The database of the National Temporal Bone Hearing and Balance Pathology Resource Registry was used to identify cases. The TB collection at the Massachusetts Eye and Ear contains 2290 TBs from 1340 individuals with well-documented clinical histories. The TB data are cataloged electronically and contain information for each specimen, including medical history, auditory data, and an overview histopathologic findings. We searched the database for individuals with a history of head injury. Relevant head injury terms were used during the search (eg, concussion, trauma, accident, head injury, traumatic brain injury, and TB fracture). Inclusion criteria included a history of head injury as documented in the donor’s medical record. Exclusion criteria included (1) history of noise exposure; (2) clinical, radiographic, or histologic TB fracture through the inner ear; (3) otologic surgery involving the middle and/or inner ear; (4) hearing loss prior to the head injury without TB fracture; (5) history of TB fracture, it can be difficult to predict whether a patient will sustain hearing loss after head injury. The terms “labyrinthine concussion,”19-21 “inner ear concussion,”22-24 “com- tion labyrinthitis,”20,25 and “otitis interna vasomoria”23 have been used in the literature since the era of Politzer,26 and are generally defined as head trauma resulting in sensorineural hearing loss without evidence of labyrinthine fracture. Reports of pathology of inner ear concussions, however, are sparse, and this term appears to be a nonspecific catchall phrase for hearing loss following head injury without TB fracture.

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Histologic Methods and Spiral Ganglion Cell Quantification

TB specimens were prepared for light microscopy by fixation in 10% buffered formalin, decalcified, and embedded in celloidin. The bones were sectioned at a thickness of 20 μm and stained with hematoxylin and eosin. Every 10th section was studied with light microscopy per the method described.27,28 The lengths of the cochlear duct and Rosenthal’s canal were calculated, and the spiral ganglion cell (SGC) population was quantified along the length of Rosenthal’s canal based on previously described methodologies.28-30 The SGC populations were then compared with age-matched controls as previously described.28 The control SGC population is based on 100 ears from individuals with useful hearing who ranged from 9 to 90 years (mean, 61 years).28 These historical controls have been used previously at our institution.31-33

Hair Cell Quantification

The presence or absence of hair cells were evaluated and reconstructed via cytocochleogram by trained otopathologists (R.I., A.K.R., J.B.N., E.D.K.). Furthermore, the (inner and outer) pillar cells, which form the tunnel of Corti where nerve fibers of cochlear nerve pass, were assessed. Normally, hair cells consist of 1 row of inner hair cells and 3 rows of outer hair cells. As described by Mahmud et al,31 the quantification of hair cell loss was done by creating 3 bins for each turn: basal (0-16 mm), middle (16-22 mm), and apical (22 mm to apex). Afterward, the total hair cell number for every turn of the cochlea was calculated separately and compared (by percentage) with the normal hair cell number, as previously calculated. The percentage of hair cell loss was described according to 4 groups: severe, a loss of 67% to 100%; moderate, 33% to 67%; mild, 1% to 33%; and none, no loss of hair cells.31

Stria Vascularis and Reissner’s Membrane Evaluation

The cross-section area of the stria vascularis was evaluated. Atrophy of the stria was determined by estimation of the percentage loss of the longitudinal volume of area in each section, as previously described.34 The percentage atrophy of the stria was summarized in every turn of the cochlea, and the results were described in 5 groups: severe, 75% to 100% area loss; moderate-severe, 50% to 75%; moderate, 25% to 50%; mild, 1% to 25%; and no atrophy.31

Hydrops in the cochlear duct was defined according to the grading scale from Cureoglu et al.35 This scale is based on the position of Reissner’s membrane (RM) and ranged from slight bulging to a <90° or >90° angle of RM with the osseous spiral lamina.

Cytocochleogram and Descriptive Analysis

Data, including SGCs, hair cells, pillar cells, and stria vascularis, were applied to MATLAB software (version 8.4, R2014b) to develop a cytocochleogram in which loss was demonstrated by black ink filling. Spiral ganglion counts for cases were compared with historical aged-matched controls.28

Computed Tomography

Postmortem computed tomography of TBs were reviewed for middle and inner ear pathology.

Results

Demographics and Clinical History

Five patients (4 men and 1 woman) met initial inclusion and exclusion criteria. Of the 10 possible TBs, 4 were excluded for the following reasons: missing TB (case 2, right side), sudden sensorineural hearing loss post–head trauma (case 3, left side), viral labyrinthitis precluding the head trauma (case 4, left side), and damage to the cochlea during the removal process (case 5, Institutional Review Board. The study was approved by the Massachusetts Eye and Ear
right side). Six TBs met inclusion and exclusion criteria. The patient representing cases 1R and 1L experienced multiple head injuries during his childhood (unknown age); for the other 4 cases, head injury occurred at an average age of 57 years (range, 34-78 years; Table 1). The average age of death was 81 years (range, 66-96 years), and the average time elapsed between the injury and death was 19 years (range, 5-37 years).

Histories of head injuries were described for all individuals: multiple concussions during childhood (case 1), concussion after seizure (case 2), fall from a flight of stairs (case 3), fall that caused frontal head injury (case 4), and cerebral concussion with coma (case 5). None of the subjects had evidence of acute or healed TB fracture per history or otopathologic evaluation in the affected ears. Additional history and findings are summarized in the Supplemental Material (available in the online version of the article).

**Audiometric Hearing Level**

All subjects had an available post–head injury audiogram that showed a range of hearing impairment, from mild to profound sensorineural hearing loss (Table 1; Figures 1A, 2). Configuration patterns of the audiograms included mild to severe down-sloping hearing loss for 4 cases (1R, 3R, 4R, 5L) and profound hearing loss at all frequencies for 2 cases (1L and 2L). Audiograms were performed at an average of 8 years after the head injury (range, 0-19 years).

**Hair Cells and Pillar Cells**

Cases 1L and 2L demonstrated severe loss of inner and outer hair cells and pillar cells along the length of the cochlea (Figures 1A, 2). The remainder 4 cases (3R, 5L, 1R, 4R) showed moderate to severe loss at the basal turn of the cochlea (segment I, which refers to 0-16 mm) and mild to moderate loss at the middle turn of the cochlea (16-22 mm; with or without pillar cell involvement) to the apex (22 mm to apex; Figures 1A, 3-5).

**SGC Quantification and Association with Hearing Loss**

All 6 cases had a decreased number of total SGCs, with an average loss of 53% (range, 25%-79%) versus historical normative age-matched controls (n = 28). The SGC count loss along all parts of the Rosenthal’s canal (segments I-IV) was evenly distributed (Table 2; Figure 1B).

**Stria Vascularis Quantification and Presence of Endolymphatic Hydrops**

Of the 6 cases, 2 (33%; 1L and 2L) demonstrated severe atrophy (75%-100%) of all 3 layers of the stria vascularis (marginal, intermediate, and basal; Figures 1A, 2) along all turns of the cochlea (basal, middle, and apical), in addition to moderate to severe atrophy of the spiral ligament (Figure 1C). Two cases (33%; 3R and 5L) showed scattered moderate degeneration (25%-50%) along all turns of the cochlea (Figures 3, 5), and the last 2 cases (33%; 1R and 4R) presented with only mild degeneration (1%-25%) of the stria vascularis, prominently at the basal and apical turns of the cochlea (Figures 1A, 4). Furthermore, 3 of 6 cases (1L, 2L, and 3R) had cochlear endolymphatic hydrops (Figure 1D).

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**Table 1. Clinical History.**

<table>
<thead>
<tr>
<th>Case (Side)</th>
<th>Age, y (Sex)</th>
<th>Trauma (Age, y)</th>
<th>HL at Last Audiogram (Age, y)</th>
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<tr>
<td>1 (R)</td>
<td>92 (M)</td>
<td>Concussions (NA, child)</td>
<td>Moderate (79)</td>
</tr>
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<td>1 (L)</td>
<td>92 (M)</td>
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<td>Profound (79)</td>
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<tr>
<td>2 (L)</td>
<td>71 (F)</td>
<td>Concussion (34)</td>
<td>Profound (71)</td>
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<tr>
<td>3 (R)</td>
<td>66 (M)</td>
<td>Fall (61)</td>
<td>Mild (63)</td>
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<tr>
<td>4 (R)</td>
<td>96 (M)</td>
<td>Fall (78)</td>
<td>Moderate (95)</td>
</tr>
<tr>
<td>5 (L)</td>
<td>72 (M)</td>
<td>MVA (57)</td>
<td>Moderate (69)</td>
</tr>
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**Table 2. Length of the Cochlear Duct, Rosenthal’s Canal, and SGC Counts.**

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<thead>
<tr>
<th>Case (Side)</th>
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<tr>
<td></td>
<td>Total Segment I</td>
<td>Segment II</td>
<td>Segment III</td>
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<tr>
<td>1 (R)</td>
<td>32.4</td>
<td>15.0</td>
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<tr>
<td>1 (L)</td>
<td>32.2</td>
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**Table 2. Length of the Cochlear Duct, Rosenthal’s Canal, and SGC Counts.**

Abbreviations: F, female; HL, hearing loss; L, left; M, male; MVA, motor vehicle accident; NA, not applicable; R, right.
Computed Tomography

There was no evidence of TB fracture in case 1, which was the only postmortem scan available for review.

Discussion

This is the first contemporary otopathology study to investigate a series of human TB from individuals with a history of head injury without evidence of TB fractures. Major findings included moderate to severe degeneration of SGCs in all cases as compared with age-matched controls. Hair cell loss, with or without pillar cell loss, was also found in several cases. Cochlear endolymphatic hydrops was identified in half the examined cases. When the TBs from the same individual (cases 1L and 1R) were analyzed, both demonstrated severe SGC loss (79% and 67%, respectively) as compared with age-matched controls. Degeneration of the hair cells and atrophy of the stria vascularis were found as well throughout the cochlea in case 1L and limited to its basal turn in case 1R.

Auditory dysfunction from major head trauma resulting in a TB fracture has been well described. In particular,
individuals with auditory dysfunction from head injury suffer from hearing loss, tinnitus, and hyperacusis. Such auditory symptoms have a significant impact on quality of life. Following head injury, many individuals suffer from debilitating tinnitus as well as difficulty hearing in loud environments.

Auditory dysfunction resulting from head injury without TB fracture, however, has been underinvestigated. Dating back to the descriptions of boxers afflicted with punch drunk syndrome in the 1920s (later known as dementia pugilistica), individuals with a history of head trauma have indicated symptoms of auditory dysfunction. Proposed mechanisms for traumatic auditory injury include an excessive fluid wave in the inner ear, stretching or tearing of the cochlear nerve, trauma to the membranous labyrinth, development of endolymphatic hydrops, and injury to the central auditory pathway (eg, inferior colliculi or at the upper pontine level). More recently, it has been hypothesized that proinflammatory mediators induced by the trauma can infiltrate into the cochlea through the round window membrane, stapes footplate, and the thin bone of the otic capsule. Despite the multitude of theories on the etiology of auditory dysfunction, scant data on human otopathology exist. Furthermore, the limited pathologic data have made it difficult to pinpoint the exact or potentially multiple mechanisms by which head trauma results in auditory dysfunction, and as a result, there are limited treatment options.

Various terms, such as inner ear concussion, have been given to the clinical observation of hearing loss following head trauma without fracture through the petrous pyramid. A host of historical clinical studies, largely from the early and mid-20th century, addressed this subject, including those by Polizter, Schwartze, Wittmaack, Voss, Brunner, and Schuknecht. However, many lacked rigorous methods of diagnosing TB fractures, such as high-resolution imaging, and were not able to provide pathologic correlation. Indeed, it is difficult to fully interpret historic studies, as TB fractures may have been missed with plain film imaging. Furthermore, a limited number of contemporary studies examined clinical symptoms among patients with a history of head trauma without TB fracture, and human otopathologic findings are exceedingly rare.

Findings from our study support previous clinical evidence indicating that hearing loss may occur in pediatric and adult patients as a result of head injury that is not severe enough to cause a TB fracture. However, the incidence and severity of hearing loss after head injury remain controversial. Browning et al studied 130 patients with head injury and did not find significant hearing loss by pure tone thresholds as compared with controls. The
mechanisms of injury in these studies were predominantly low impact. In contrast, Karch et al. Podoshin et al, and Griffiths et al found that 18% to 58% of people with severe head trauma and evidence of brain injury had significant hearing loss. The mechanism of injury and the severity of head trauma therefore may affect the incidence and severity of the resultant hearing loss.

The etiology for SGCs and hair cell loss is currently unknown. It is possible that SGC loss is secondary to hair cell loss or a primary consequence of head trauma. Animal models of head injury have also been used to study the auditory pathway and may provide some insight. Stenger and Linck developed a rat model that showed signs of inner ear hemorrhage affecting the labyrinth and cochleovestibular nerve in the internal acoustic canal. Kimura employed a guinea pig model to demonstrate that an obstruction of the endolymphatic sac led to severe dilatation of the endolymphatic duct. Brunner et al also utilized a guinea pig head injury model and demonstrated inner ear hemorrhage, which was believed to be the reason for hearing loss.

In a head trauma model of the cat, Wittmaack hypothesized that hearing loss was due to a traveling pressure wave that resembled an acoustic insult, resulting in direct injury of the organ of Corti and SGCs. SGCs became vacuolated and were severely degenerated 2 weeks following injury. Notably, the most severe injury was in the middle turn, followed by the apical turn, and least severe in the basal turn of the cochlea. Schuknecht and Davison also evaluated the hearing levels and histologic changes in 10 cats following a blow to the head. The primary pathologic finding was damage of the outer hair cells in the basal turn of the cochlea. The location of the damage corresponded to hearing loss in frequency ranges from 2000 to 8000 Hz. These findings lend support to the theory that hair cell loss may be secondary to an acoustic wave transmitted via bone conduction to the basal turn of the cochlea. Interestingly, significant nerve degeneration (decreased SGC count) corresponding to severe hearing loss was found only in cats who were sacrificed 3 or more weeks after the head trauma. It is possible that routine histological methods may not necessarily reflect the pathological changes in cases that the trauma was close to the time of the death (less than 3 weeks).

The study has several notable limitations that are critical to highlight. First, the results cannot be generalized to all head injury cases. In this retrospective otopathologic study, a relatively small number of subjects were evaluated. The mechanism and degree of trauma varied widely. Second, similar to all otopathology studies, the information from the clinical history may have been incompletely reported. Minor head injury may have not been fully recorded for
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specimens in other collections. Additional unknown factors between time of injury and time of death may have resulted in the otopathologic changes. However, no other otologic disorders that may have resulted in hearing loss were reported. The hearing tests were performed in some cases many years before death, so the correlation between histologically assessed cochlear abnormalities and the hearing performance cannot be seen as causative. Also, unfortunately, in 2 cases (2L and 5L), the contralateral TB specimens were not available for histopathology study, and the patients’ hearing loss was noted years after the head injury; therefore, the hearing loss cannot be fully attributed to the trauma. Third, although noise exposure was not reported in the medical history, its effect cannot be fully excluded due to the retrospective nature of this study. Fourth, similar to all types of cell counts and subjective analysis of pathologic specimens, there may be some degree of variability. Nevertheless, the study was performed and reviewed by individuals with extensive otopathology experience (R.I. and J.B.N.). Last, the peripheral vestibular system of the patients is yet to be fully studied, and future investigations may address vestibular otopathology. Despite limitations, this study provides rare human TB data that contribute to understanding the pathophysiology of human head injury and auditory dysfunction.

Conclusions

Otopathologic analysis of patients with a history of head injury demonstrates cochlear pathology, even in the absence of TB fracture. These findings have implications for understanding the mechanisms of hearing loss in patients following head injury. Given extended duration between time of injury to death, further studies are necessary to determine if otopathology findings are directly attributable to trauma.

Acknowledgments

We thank Dr Alessa Colaianni of the Harvard Department of Otolaryngology for her careful review of the manuscript. We also thank Barbara Burgess, Diana Jones, Jenifer O’Malley, and Meng Yu Zhu for their skillful histologic preparation of the specimens, as well as Garyfallia Pagonis for her expert assistance in preparation of the figures.

Author Contributions

Reuven Ishai, conception, design, execution and analysis, drafting, revision and approval; Renata M. Knoll, design, execution, drafting, revision and approval; Jenny X. Chen, conception, design, execution, drafting, revision and approval; Kevin Wong, design, execution and analysis, drafting, revision and approval; Katherine L. Reinshagen, design, execution and analysis, drafting, revision and approval; Joseph B. Nadol Jr, design, execution and analysis, drafting, revision and approval; Aaron K. Remenschneider, conception, design, execution and analysis, drafting, revision and approval; David H. Jung, conception, design, execution and analysis, drafting, revision and approval.

Disclosures

Competing interests: None.
Sponsorships: None.
Funding source: NIDCD (NIH) L124DC013983.

Supplemental Material

Additional supporting information is available in the online version of the article.

References


