







## ORIGINAL RESEARCH

# Long-term cochlear implantation outcomes in patients following head injury

Rory J. Lubner BS<sup>1,2,3</sup>  | Renata M. Knoll MD<sup>1,2</sup>  |  
 Danielle R. Trakimas MD, MSE<sup>1,2,4</sup> | Ryan A. Bartholomew MD<sup>1,2</sup>  |  
 Daniel J. Lee MD<sup>1,2</sup> | Brad Walters PhD<sup>5</sup> | Joseph B. Nadol Jr. MD<sup>1,2</sup>  |  
 Aaron K. Remenschneider MD, MPH<sup>1,2,6</sup>  | Elliott D. Kozin MD<sup>1,2</sup> 

<sup>1</sup>Department of Otolaryngology, Massachusetts Eye and Ear, Boston, Massachusetts

<sup>2</sup>Department of Otolaryngology, Harvard Medical School, Boston, Massachusetts

<sup>3</sup>Warren Alpert Medical School of Brown University, Providence, Rhode Island

<sup>4</sup>Department of Otolaryngology, Johns Hopkins Medical School, Baltimore, MD

<sup>5</sup>Department of Otolaryngology, University of Mississippi Medical Center, Jackson, Mississippi

<sup>6</sup>Department of Otolaryngology, University of Massachusetts Medical Center, Worcester, Massachusetts

**Correspondence**

Aaron K. Remenschneider and Elliott D. Kozin, 243 Charles Street, Boston, MA 02114.  
 Email: aaron\_remenschneider@meei.harvard.edu (A. K. R.) and elliot\_kozin@meei.harvard.edu (E. D. K.)

**Abstract**

**Objective:** In cases of a severe to profound sensorineural hearing loss following head injury, the cochlear implant (CI) is the primary option for auditory rehabilitation. Few studies, however, have investigated long-term CI outcomes in patients following head trauma, including those without temporal bone fracture (TBF). Herein, the aim of this study is to examine CI outcomes following cases of head injury with and without TBF.

**Methods:** Audiometric outcomes of patients who received a CI due to a head injury resulting in severe to profound hearing loss at two tertiary care hospitals were analyzed. Patients were divided into those who received a CI in a fractured temporal bone (group A, n = 11 patients corresponding to 15 ears) and those who received a CI in a non-fractured temporal bone (group B, n = 8 patients corresponding to nine ears). Primary outcomes included duration of deafness prior to CI and postoperative consonant-nucleus-constant whole word (CNC) scores.

**Results:** Nineteen patients (84% male), corresponding to 24 CIs, were identified. Fifteen CI were performed on ears with TBF (group A), and nine CI were performed on ears without TBF (group B). No patients had an enlarged vestibular aqueduct (EVA). The mean duration of deafness was 5.7 and 11.3 years in group A and group B, respectively. The mean duration of CI follow-up (CI experience) was 6.5 years in group A and 2.1 years in group B. The overall mean postoperative CNC score for all subjects was 68.6% ( $\pm 21.2\%$ , n = 19 with CNC testing). There was no difference in CNC score between group A and group B (69.8% and 66% respectively,  $P = .639$ ).

**Conclusion:** The study is among the largest series examining long-term outcomes of CI after head injury. CI is an effective method for auditory rehabilitation in patients after head injury.

**Level of evidence:** IV.

Rory J. Lubner and Renata M. Knoll contributed equally to this study.

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## KEYWORDS

cochlear implant, cochlear implantation, head injury, temporal bone fracture

## 1 | INTRODUCTION

Head injury is a major worldwide public health concern. According to data from the United States Centers for Disease Control and Prevention, 1.7 million people sustain a traumatic brain injury (TBI) in the United States alone each year.<sup>1</sup> The leading causes of head injury in the United States are falls (35%), motor vehicle-related injuries (17%), and strikes or blows to the head from or against an object (17%).<sup>1</sup> Approximately 4% to 30% of these injured individuals have skull fractures, in which 14% to 22% sustain temporal bone fractures (TBF).<sup>2-6</sup> Most of these fractures result from high-energy trauma, and can be detected on high resolution computed tomography (CT) of the temporal bone.

Hearing loss has long been recognized as a consequence of head injury. Auditory symptoms are estimated to occur in 10% to 60% of patients following head injury.<sup>7-15</sup> In cases of more severe forms of head injury with concurrent TBF, hearing loss is thought to be caused by direct anatomic disruption of the middle ear and/or inner ear sensory neuroepithelium.<sup>16-20</sup> In the absence of a TBF, it can be difficult to predict whether a patient will sustain auditory pathology. Various terms, such as "inner ear concussion" and "labyrinthine concussion", have been given to the phenomenon of auditory dysfunction following head trauma without TBF fracture. Historic human otopathology and animal experiments by Polizter,<sup>21</sup> Schwartze,<sup>22</sup> Wittmaack,<sup>23</sup> Voss,<sup>24</sup> Brunner,<sup>25</sup> and Schuknecht<sup>26</sup> proposed various sources of auditory dysfunction following labyrinthine concussion including inner ear hemorrhage, stretching of the cochlear nerve,<sup>27</sup> and traveling pressure wave.<sup>26</sup>

For patients sustaining head injury with resultant severe to profound sensorineural hearing loss (SNHL) and an intact cochlear nerve, cochlear implantation (CI) is the primary option for auditory rehabilitation. Previous studies have reported the successful implantation and auditory rehabilitation of post linguallly deaf patients following head injury.<sup>28-45</sup> However, most of these studies are limited by small sample sizes, short follow-up periods, and heterogeneous audiometric outcome metrics.<sup>30-33,44-46</sup> Herein, the aim of this study is to evaluate the long-term auditory outcomes of CI following head injury in patients with and without TBF using word recognition testing.

## 2 | METHODS

### 2.1 | Study design and participant selection

A retrospective analysis of medical records at two tertiary care centers of patients who underwent a CI procedure following head injury was completed. Inclusion criteria included patients with severe to

profound SNHL due to head injury who received a CI for auditory rehabilitation. Exclusion criteria included prior SNHL or hearing loss due to other otologic diseases, such as chronic otitis media, otosclerosis, Meniere's disease, sudden SNHL, congenital hearing loss, and/or meningitis before or after the head injury. The study was approved by the Massachusetts Eye and Ear Infirmary and University of Massachusetts Institutional Review Boards.

### 2.2 | Patient chart review

Patient records were reviewed and demographic features, age at trauma, age at CI surgery, mechanism of injury, side and orientation of fracture if present (transverse vs longitudinal), otic capsule involvement, bilateral preoperative pure tone average (PTA), duration of deafness and preoperative promontory stimulation were recorded (if available). Patients were subdivided into two groups: patients who received a CI in an ear with a TBF (group A) and patients who received a CI in an ear without TBF (group B). For those patients who had a history of more than one head trauma event, the age at the time of the first episode was considered for the analysis. Deafness duration was defined as the time in years between the date of the CI procedure and the age at which sudden hearing loss due to trauma occurred, or in progressive cases, the age at which they were unable to benefit from hearing aids.

Operative records were reviewed to ascertain details of the implantation procedure, such as intraoperative findings, type of CI device, and type and extent of electrode insertion, duration of CI experience and postoperative CI performance using word recognition testing. Consonant-nucleus-consonant (CNC) monosyllabic words were evaluated when available. Scores are reported as the percentage of correctly repeated words and individual phonemes. Medical records and available imaging were also reviewed for evidence of an enlarged vestibular aqueduct (EVA).

### 2.3 | Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics (version 24.0; Armonk, NY). Differences in CNC between those who did and did not have TBF were tested using the Mann-Whitney *U* Test. A *P*-value <.05 was considered statistically significant.

## 3 | RESULTS

### 3.1 | Participant and injury characteristics

Nineteen patients (84% male) met inclusion and exclusion criteria. The mean age at injury was 29.7 years (range: 16-65) in group A, and

28.7 years (range: 7-62) in group B. Twenty ears from 12 patients (63%) presented with TBF. Eight patients (42%) had bilateral TBF, and four (21%) had unilateral fractures. A transverse fracture with otic capsule violation was described in eight patients, and one patient presented with a longitudinal fracture sparing the otic capsule. In terms of associated injuries, two patients in group A (subject 2 and 3) had a CSF leak from the injury. Additionally, two patients (subject 1 and 3) had dense right sided facial paralysis from the head impact. Demographic data and clinical history of the patients are shown in Table 1. No patients had EVA documented in their medical history.

### 3.2 | Preoperative audiometric evaluation

Five patients received bilateral implants, leading to a total of 24 CI procedures. Of the twenty ears (12 patients) with TBF, 15 of them

received CI on the fractured side (group A, n = 15 ears). The remaining nine CI were performed on ears without TBF (group B, n = 9 ears). The mean age of patients at CI surgery was 34.9 years (range: 19-66 years) in group A and 44.2 years (range: 21-68) in group B, and the mean duration of deafness was 5.7 years (range: 0.4-24) in group A and 11.3 years (range: 0.4-44) in group B. Preoperatively, 15 patients had bilateral severe to profound SNHL, while four patients had unilateral profound SNHL, with PTA  $\geq$ 90 dB in the affected ear. Although subject 1 and 4 did not have a preoperative audiogram available for our review, the medical records reported bilateral anacusis after fracture. Four cases in group A had preoperative CNC scores in the implanted ear available for review, of which three had a CNC score of 0% (range: 0%-2%), and four cases in group B also had preoperative CNC scores, of which two had a CNC score of 0% (range: 0%-4%). Preoperative promontory stimulation with a transtympanic needle was described in the medical records for three patients (subject

**TABLE 1** Clinical history

Subject	Sex	Age (y) <sup>a</sup>	Cause of trauma	Implanted side	Right ear	Left ear	PTA right ear <sup>b</sup>	PTA left ear <sup>b</sup>
1	M	26	MVA	Right	Tr/Otic capsule-involving	Tr/Otic capsule-involving	Unknown	Unknown
2	F	44	Fall	Right	Tr/Otic capsule-involving	—	>120	17
3	M	31	Fall (stairs)	Left	Tr/Otic capsule-involving	Tr/Otic capsule-involving	>120	>120
4	M	35	MVA	Bilateral	Tr/Otic capsule-involving	Tr/Otic capsule-involving	Unknown	Unknown
5	F	16	MVA	Bilateral	TBF, type unknown	TBF, type unknown	90	110
6	M	35	Hit by a metal pipe	Left	Tr/Otic capsule-involving	Tr/Otic capsule-involving	>120	110
7	M	25	Fall/assault	Bilateral	TBF, type unknown	TBF, type, unknown	>120	>120
8	M	19	fall from height	Bilateral	Tr/Otic capsule-involving	Tr/Otic capsule-involving	112	95
9	M	32	MVA	Left	—	Tr/Otic capsule-involving	10	>120
10	M	65	Fall	Right	Lo/otic capsule-sparing	—	110	28
11	M	22	MVA	Left	TBF, type unknown	TBF, type unknown	NR	99
12	F	56	Assault	Right	—	—	NR	86
13	M	<sup>c</sup>	MVAs/Assault	Bilateral	—	—	84	NR
14	M	4	MVA	Left	—	—	85	95
15	M	7	Fence fell on him	Right	—	—	85	94
16	M	<sup>c</sup>	MVA/Fall(stairs)	Left	—	—	60	68
17	M	28	MVA	Right	—	—	113	5
18 <sup>d</sup>	M	18	MVA	Right	—	Tr/Otic capsule-involving	112	NR
19	M	7	Unknown	Right	—	—	85	68

Abbreviations: —, no TBF; F, female; Lo, longitudinal fracture; M, male; PTA, pure-tone average; Tr, transverse or mixed fracture; TBF, temporal bone fracture; y, years; Unknown, information not available on medical records.

<sup>a</sup>Age at trauma.

<sup>b</sup>Preoperative.

<sup>c</sup>Not applicable, multiple head traumas.

<sup>d</sup>While having a transverse fracture in the L temporal bone, subject 18 was implanted in the right, non-fractured temporal bone.

**TABLE 2** Summary of implanted ears

Subject	Group	Side	Age at surgery	Duration of deafness (y)	Cochlear implant device	CI Approach	Extent of insertion	Intraoperative findings	Postoperative complications
1	Group A	Right	27	<1	Cochlear Nucleus 22	CO	Partial <sup>a</sup>	Cochlear ossification	None
2	Group A	Right	46	2.8	Med-el Concert Flex 28	RW	Full	Microfracture of RW	None
3	Group A	Left	33	2	Cochlear Nucleus CI512 with Contour Adv	CO	Full	Fibrosis in the proximal basal turn	None
4	Group A	Right	35	0.6	Advanced Bionics—HiRes 90K/Hifocus	No info	Partial	Unknown	None
4	Group A	Left	35	0.9	Advanced Bionics—HiRes 90 K/Hifocus	No info	Partial	Unknown	None
5	Group A	Right	38	22	Advanced Bionics HiRes 90K/HiFocus	CO	Partial	Adhesions in the round window niche	Facial nerve stimulation <sup>b</sup>
5	Group A	Left	30	14	Advanced Bionics—Clarion—C II HiFocus	Extended RW	Full	Fibrosis in the basal turn and scala tympani	None
6	Group A	Left	34	1.1	Advanced Bionics—Clarion—C II HiFocus	CO	Full	None	None
7	Group A	Right	28	3.6	Ineraid Symbion implant	Extended RW	Full	None	None
7	Group A	Left	49	24	Cochlear Nucleus 24	CO	Full	None	Wound dehiscence
8	Group A	Right	19	0.6	Cochlear Nucleus 24	CO	Full	Fracture through RW	None
8	Group A	Left	19	0.6	Cochlear Nucleus 24	CO	Full	Fracture through RW and promontory	None
9	Group A	Left	32	0.4	Cochlear Nucleus CI532	extended RW	Full	None	None
10	Group A	Right	66	1.1	Advanced Bionics—HiRes Ultra with Mid-Scala	CO	Full	None	None
11	Group A	Left	32	11	Advanced Bionics—Clarion—C II HiFocus	CO	Full	None	None
12	Group B	Right	68	12	Cochlear Nucleus CI532	Extended RW	Full	None	None
13	Group B	Right	45	0.5	Cochlear Nucleus Freedom	CO	Full	None	None
13	Group B	Left	38	6	Cochlear Nucleus Freedom	No info	Full	Unknown	Unknown
14	Group B	Left	21	17	Advanced Bionics HiRes 90K 1J	CO	Full	None	None
15	Group B	Right	51	44	HiRes 90K/HiFocus	CO	Full	None	None
16	Group B	Left	64	3	Medel Mi1200 PIN +FLEX28	RW	Full	None	None
17	Group B	Right	28	0.4	Cochlear Nucleus CI532	Extended RW	Full	None	None

**TABLE 2** (Continued)

Subject	Group	Side	Age at surgery	Duration of deafness (y)	Cochlear implant device	CI Approach	Extent of insertion	Intraoperative findings	Postoperative complications
18	Group B	Right	37	19	90K HiFocus/Helix	CO	Full	None	None
19	Group B	Right	46	0.4	Cochlear Nucleus CI522	RW	Full	None	None

Note: Preoperative promontory stimulation was reported in the medical records for subject 5L, subject 6L, and subject 7R only, and all presented with normal electrical responses.

Abbreviations: CO, cochleostomy; NR, not registered (thresholds greater than audiometer's measuring capability); PTA, pure-tone average; RW, round window; Unknown, information not available on medical records; y, years.

<sup>a</sup>Retrograde electrode insertion.

<sup>b</sup>Occasional twitch around mouth.

5L, subject 6L, and subject 7R) to detect the viability and function of the eighth nerve, with evidence of normal electrical responses in all cases.

In the four TBF cases with bilateral TBF, the PTA of the contralateral, non-implanted ear was either unknown (subject 1) or greater than 100 dB (subject 3, 6, and 11). Of the four TBF cases with unilateral TBF, all of the contralateral ears had a preoperative PTA of less than 30 dB.

### 3.3 | Intraoperative findings and postoperative complications

In terms of intraoperative findings, 20 operations had complete insertion of the electrode arrays and four cases had a partial insertion. Of the cases of partial insertion, all had a TBF on the side of implant. One patient required a drill out due to cochlear ossification (subject 1, group A). Nine (60%) CI cases in group A were placed with a cochleostomy approach, three (20%) were placed by an extended RW approach, and one (6.7%) was placed by a RW approach.

The most common intraoperative finding was a fracture line through the round window (12.5%, subject 2 and subject 8 R/L), followed by fibrosis in the basal turn of the cochlea (8.3%, subject 3 and subject 5L). Cochlear ossification was reported only in one patient (subject 1, group A). Minor facial nerve stimulation was reported for subject 5R and subject 7L presented with postoperative wound dehiscence. Minor facial nerve stimulation resolved 10 weeks postoperatively. None of the other 17 patients reported postoperative complications. The summary of implanted ears is shown in Table 2.

### 3.4 | Postoperative audiometric outcomes

The mean CI experience time at testing was 4.9 years (range: 0.1-22 years). The mean postoperative CNC score in group A and group B were 69.8% ( $\pm 15\%$ ,  $n = 13$  with CNC testing) and 66% ( $\pm 32.6\%$ ,  $n = 6$  with CNC testing), respectively ( $P = .639$ ). One patient

**TABLE 3** CI results

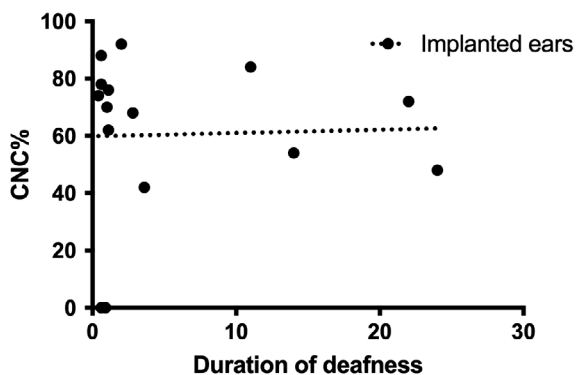
Subject	Side	CNC		CI experience at time of testing (y)
		Word (%)	Ph (%)	
1	Right	70	84	22
2	Right	68	83.3	1.2
3	Left	92	97	6.2
4	Right	— <sup>a</sup>	—	3
4	Left	— <sup>a</sup>	—	3
5	Right	72	86	5.2
5	Left	54	71	14.7
6	Left	76	91	2.2
7	Right	42	70	19.6
7	Left	48	70	3
8	Right	78	92	2.2
8	Left	88	93	2.2
9	Left	74	87	0.5
10	Right	62	83.3	0.3
11	Left	84	93	13
12	Right	26	55	1.3
13	Right	88	95	0.3
13	Left	90	97	7.3
14	Left	Monosyllabic words: 37.5%		0.3
15	Right	22	53	4
16	Left	Monosyllabic words: 33.3%		0.1
17	Right	84	95	0.5
18	Right	86	94	5
19	Right	AzBio in quiet score: 60%		0.1

Abbreviations: CNC, consonant-nucleus-consonant speech test; Ph, phonemes; y, years.

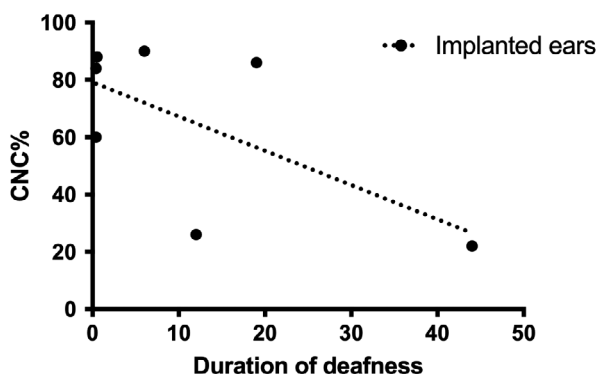
<sup>a</sup>Neural response testing was performed with no response noted.

(subject 4) did not gain any benefit from implantation, with no responses after neural response testing. CT scan images showed bilateral labyrinthitis ossificans with a few electrodes within the cochlea, and the patient was referred for an auditory brainstem implant

## (A) Duration of deafness vs CNC score in Group A



## (B) Duration of deafness vs CNC score in Group B



**FIGURE 1** Relationship between deafness duration and CNC score in patients: A, with TBF (group A), and B, without TBF (group B). CNC, consonant-nucleus-consonant; TBF, temporal bone fracture

evaluation. Subjects 14 and 16 were tested with Early Speech Perception monosyllabic words, scoring 37.5% and 33.3%, respectively. Subject 19 was tested with AZ bio in quiet, scoring 60%. Patients with unilateral hearing loss who underwent cochlear implantation ( $n = 3$ ) had a mean postoperative CNC score of 75.3%. Speech comprehension outcomes for CI recipients are shown in Table 3.

The relationship between duration of deafness and CNC scores are depicted in Figure 1. While the bivariate correlation between deafness duration and CNC score in group A and group B were both non-significant ( $P = .908$  and  $P = .125$ , respectively), group B's correlation coefficient ( $r = -.635$ ) was moderately negative, while group A's coefficient ( $r = .033$ ) was weakly positive.

## 4 | DISCUSSION

Our study is among the largest series to analyze CI outcomes following head injury with and without TBF. Overall, cochlear implantation appears to be a viable option for auditory rehabilitation in patients with severe to profound hearing loss after head injury. In 24 CIs after head injury, 83% ( $n = 20$ ) of all CI resulted in full electrode insertions. Thirty percent of patients had five or more years of audiometric follow-up, and 79% had a CNC score greater than 50% at follow-up.

Additionally, there were similar CI outcomes in patients with and without temporal bone fracture. Lastly, all patients with single sided deafness who underwent cochlear implantation had satisfactory post-operative performance.

In terms of prior studies examining audiometric outcomes following CI in patients with temporal bone fractures, the present study findings are in line with smaller case series with limited follow-up (Table 4). Camilleri et al's study was among the first to describe successful CI in a cohort of TBF patients, in which six out of the seven implants had a hearing threshold of 40 to 50 dB 9 months following implant switch-on.<sup>29</sup> Greenberg et al report CI in eight ears with TBF, and while those that were implanted had auditory improvement similar to general CI population without head injury, the authors caution that additional factors such as brain injury severity, and cognitive/behavioral impairments should guide CI patient selection.<sup>34</sup> In the 15 CI with TBF in our study, similar post-implant auditory outcomes were found over a mean follow-up period of 6.5 years compared to Greenberg et al's average follow-up period of 1 year, demonstrating the longevity of post-CI auditory outcomes.

CI in patients following head injury without TBF has also been reported in the literature (Table 4). Unfortunately, many of these studies did not do a distinct analysis of patients without TBF. Khwaja et al retrospectively reviewed 23 CI in patients following head injury, in which seven were completed on ears without TBF. While separate analyses of CI performance in patients without TBF were not included, the authors reported successful auditory rehabilitation generally, but also noted that significant increase duration of hearing loss correlated with poorer post-CI auditory outcomes.<sup>43</sup> Medina et al also included seven non-TBF CI cases following head injury in her retrospective review of cochlear and auditory brainstem implants. Similar to Khwaja et al, Medina et al did not perform any separate or comparative analyses between TBF and non TBF CI cases, but cited a mean 82% sentence recognition open set score across all CIs.<sup>39</sup> The auditory outcomes in nine CI cases following head injury without TBF in our study are both similar to our auditory outcomes in the TBF population as well as the outcomes previously reported in the literature.

Three of our patients underwent assessment with promontory stimulation which demonstrated normal electrical responses, and all three achieved significant benefit from the CI device. The promontory stimulation test aims to assess the survival of spiral ganglion cells and nerve fibers. However, promontory stimulation remains controversial due to potential for false negatives.<sup>46</sup> Serin et al<sup>35</sup> reported one patient in a series of five that, although promontory stimulation test indicated appropriate neural function in both ears, one side demonstrated limited benefit with decreasing performance in time. Greenberg et al<sup>34</sup> also described two cases with the worst performing postoperative hearing outcomes, despite a positive promontory stimulation test before implantation.

CI outcomes following head injury may have variable outcomes due to intracochlear changes that occur following head injury. A post-mortem study of the cochlea following head injury without TBF has shown that there is a range of 25% to 79% loss of spiral ganglion neurons (SGNs) compared to controls without head injury.<sup>20</sup> Similar to

**TABLE 4** Prior studies on cochlear implantation after head injury

Studies	Total number of CI	Number of non-TBF CI	Number of CI	Mean age (range)	Duration of deafness, y (range)	Cochlear implant device type (cases)	Intraoperative findings (cases)	Extent of electrode insertions (cases)	Postoperative complications (cases)	Mean follow-up time, y (range)	Speech perception test	Overall results (range)
Levine <sup>46</sup>	1	1	—	41	Unknown	Unknown	Misalignment of the inner ear structures	Full	Unusual location of the electrodes in the 2 first procedures	0.1	Not reported	<sup>a</sup>
Camilleri et al <sup>29</sup>	7	7	—	44 (13-69)	12.6 (1.7-35) 1 case unknown	Nucleus 22 (6) Ineraid (1)	Partial obliteration of the basal turn (2) Total cochlear obliteration (1)	Full (6) Partial (1)	Facial nerve stimulation (2)	0.8	AAI BKB VCV	Preoperative mean audiogram threshold: 96.57 (90-106) Mean implant-aided audiogram threshold: 44 dB (40-50) Postoperative BKB: 71 (44-100)
Simons et al <sup>30</sup>	1	1	—	25	1	Nucleus 22	None	Full	None	0.5	IST CID	Preoperative IST: 0/88 Postoperative IST: 72/88 words Preoperative CID: 1/200 Postoperative CID: 174/200
Shin et al <sup>33</sup>	1	1	—	65	0.25	HiRes 90K	None	Partial	None	1.5	Not reported	<sup>b</sup>
Greenberg et al <sup>34</sup>	11	8	3	42 (26-59)	5.6 (1-12)	Nucleus 22M (6) AB C90K (5)	Not reported	Not reported	None	1	CUNY	70% (16%-100%)
Chung et al <sup>32</sup>	2	2	—	44	0.2 (Rt) 1.2 (Lt)	Not reported	None	Full	None	1.2	APTA Open set WPT	APTA: 25 dB WPT: 100%
Serin et al <sup>35</sup>	6	5	1	37 (12-46)	1.5 (0.5-3.6)	Nucleus 24M (1) Med-el C 40+ (2) Medel Pulsar device (3)	Free blood in the cochlea (2) Flattening and displacement of the promontorium/OW and RW could not be identified (1)	Full (5) Partial (1)	Temporary facial paresis (1)	0.5-7	closed-set speech open-sentence speech	Closed set initial phoneme: 84% (4%-100%) Open sentence: 70% (0%-100%)

(Continues)

TABLE 4 (Continued)

Studies	Total number of CI	Number of TBFI	Number of non-TBFI	Mean age (range)	Duration of deafness, y (range)	Cochlear implant device type (cases)	Intraoperative findings (cases)	Extent of electrode insertions (cases)	Postoperative complications (cases)	Mean follow-up time, y (range)	Speech perception test	Overall results (range)
Zanetti et al <sup>31</sup>	2	2	—	41	0.4	Nucleus Contour Advance	None	Full	None	1.5	WRS SRS	100% (WRS and SRS)
Hagr <sup>38</sup>	6	5	1	35 (25-54)	1.5 (0.33-4)	Nucleus Freedom CI24RE	Fracture crossing the promontory and RW (1) Fibrous tissue in the RW (1)	Full	None	2.7 (1.5-5)	Not reported	<sup>b</sup>
Iacovou et al <sup>36</sup>	2	2	—	52	0.8	Not reported	Complete obliteration of the cochlea	Full	None	Not reported	Not reported	<sup>b</sup>
Vermeire et al <sup>37</sup>	4	4	—	32 (21-46)	2.1 (0.8-5.3)	Med-el C40+ (2) Nucleus CI22 (1) Laura (1)	None	Full	None	0.6-4.8	NVA	63% (24%-95%)
Plontke et al <sup>45</sup>	1	1	—	8	0.6	Nucleus System CI512	None	Full	None	0.5	Freiburger test	90%
Chen and Yin <sup>44</sup>	1	1	—	28	0.3	Med-el C40+	None	Full	None	Not reported	Not reported	<sup>b</sup>
Khawaja et al <sup>43</sup>	23	16	7	51, SD: 12.0	12 (1-30)	Freedom (6) CI124 (6) CI122 (5) CI512 (1) Med-el (2) Sonata-Flex (2) Ineraid (1)	Complete obliteration of basal turn (2)	Full (22) Partial (1)	Device infection (1)	6.9 years	BKB CUNY AB	BKB: 64% (0%-100%) CUNY: 83% (0%-100%) AB: 60% (7%-90%)
Jeon et al <sup>41</sup>	1	1	—	33	2	Nucleus CI 24 M	Fibrous band and fractured bony fragment on the tympanic cavity	Full	None	7	GASP-K	100%
Vankoevinger and Basura <sup>40</sup>	2	2	—	15	0.1	Not reported	Bilateral obliteration of the cochlear basal turn	Full	Facial nerve stimulation (1)	Not reported	Not reported	<sup>c</sup>
Medina et al <sup>39</sup>	14	9	5	51 (19-62)	Not reported	Not reported	Not reported	Full	None	4.4 (0.5-13)	SR open set	82% (30%-100%)
Espahbodi et al <sup>42</sup>	2	2	—	30	1.4	Not reported	None	Full	Facial nerve stimulation (1)	0.4	HINT	97%-98%



TABLE 4 (Continued)

Studies	Total number of CI	Number of TBF CI	Number of non-TBF CI	Mean age (range)	Duration of deafness, y (range)	Cochlear implant device type (cases)	Intraoperative findings (cases)	Extent of electrode insertions (cases)	Postoperative complications (cases)	Mean follow-up time, y (range)	Speech perception test	Overall results (range)
Lubner et al (2020)	24	15	9	38 (19-68)	7.8 (0.4-44)	Freedom (2) Cochlear Nucleus 22 (1) Cochlear Nucleus 24 (3) Med-el Flex 28 (1) CI512 (1) CI532 (3) CI522 (1) Advanced Bionics (10) Ineraid (1) Med-el Mi 1200 (1)	Cochlear ossification (1) Microfracture of RW (3) Fibrosis in basal turn (2) RW adhesions (1)	Full (20) Partial (4)	Facial nerve stimulation (1) Wound dehiscence (1)	4.88 (0.1-22)	CNC	69% (22%-92%)

Abbreviations: +, preserved auditory sensation in the ear to be implanted; AAI, implant-aided audiogram; AB, Arthur Boothroyd; AN, Antwerpen-Nijmegen battery; APTA, aided pure tone audiometry; BKB, Bench Kowel Bamford; CID, Central Institute of the Deaf Everyday Speech Sentence Test; CUNY, City University of New York sentence test; GASP-K, Glendonald Auditory Screening Procedure-Korean performance score; HINT, hearing in noise test sentences; IST, Iowa sentence test; n, number of cases; NVA, Nederlandse Vereniging voor Audiologie (monosyllabic); OW, oval window; RW, round window; SR, sentence recognition open set; SRS, sentences recognition scores; University of New York sentences; TBF, temporal bone fracture; VCV, vowel-consonant-vowel; WPT, word perception tests; WRS, word recognition scores.

<sup>a</sup>Patient had reasonable thresholds.

<sup>b</sup>Patient was able to understand speech and use the telephone.

<sup>c</sup>Patient had normal thresholds at all frequencies bilaterally.

other historic reports in fractured temporal bones,<sup>47,48</sup> Nadol et al<sup>49</sup> found an average survival of SGNs of 11468 in four specimens with TBF. Moreover, Morgan et al<sup>50</sup> described a patient with bilateral transverse TBF, in which the side with a lower number of SGNs was related to extensive labyrinthine ossification, with a total of 11 799 cells, while on the contralateral side the total count of ganglion cells was 24 615. Although the loss of SGNs reached up to two thirds of the normal range in these studies, it seems that even relatively poor ganglion cell survival can generate beneficial auditory sensation after CI.<sup>51,52</sup>

Beyond SGN survival, cochlear ossification or fibrosis may inhibit or prevent a successful insertion of the implant electrodes, leading to variable CI performance.<sup>44</sup> In cases of TBF, the basal turn of the cochlea at the scala tympani is reported as the most common site of ossification.<sup>50,53,54</sup> Alternative techniques for implant placement might be necessary, in which drilling out the obliterated portion of the cochlea, scala vestibule insertion, and using double arrays are reasonable options.<sup>29,55</sup> In a small series with seven patients reported by Camilleri et al,<sup>29</sup> partial ossification in the basal turn of the cochlea was found in two cases and a cochleostomy was required. They were both successfully benefited from the CI even though only a partial electrode insertion was achieved. The authors reported only one case in their series presenting with total obliteration of the cochlea, in which the CI performance was poor, and the patient had to be explanted due to associated facial nerve stimulation. Iacovou et al<sup>36</sup> reported another case with bilateral TBF presenting with complete ossification of the scala tympani and vestibuli of the cochlea on one side, preventing implantation. Partial obliteration of the basal turn requiring an extended cochleostomy was also reported in one patient by Vankoeving and Basura,<sup>40</sup> in which the insertion of the electrodes went uneventfully through the lumen of the scala tympani.

In addition to cochlear ossification or fibrosis resulting from TBF, it can also occur due to the CI procedure itself. It has been previously demonstrated that intracochlear ossification can occur following CI in patients without TBF.<sup>56</sup> Trakimas et al<sup>19</sup> examined the temporal bones of two patients with bilateral TBF and unilateral CI performed 0.5 and 6 years following the traumatic incident, and cited greater intracochlear ossification on the implanted side in both cases compared with the fractured temporal bone without CI. Additionally, this study suggests that TBF is not always associated with intracochlear ossification and that full insertion of CI in TBF patients is possible, even years after the initial injury, as there was no evidence of labyrinthitis ossificans on the non-implanted TBFs, as well as no apparent damage to the osseous spiral lamina either to the implanted or the non-implanted TBFs. Patients in our study also demonstrate that full CI insertion may be possible years after injury.

The candidacy criteria for CI have been expanded in the last few years. While CI for single-sided deafness was first introduced in the setting of intractable tinnitus,<sup>57,58</sup> recent studies have demonstrated it to be beneficial far beyond tinnitus suppression.<sup>59-61</sup> Of the currently available treatment options for single-sided deafness, contralateral routing of sound (CROS), osseointegrated implants (OI)/bone anchored hearing aids (BAHA) devices are the most frequently used.<sup>62</sup> However, while these options fail with regards to restoring binaural

sound processing, sound localization and tinnitus suppression, CI may overcome these issues.<sup>59,63</sup> Plontke et al<sup>45</sup> reported a case of an 8-year-old child with traumatic single-sided deafness treated with CI despite normal hearing in the contralateral ear. In addition to good speech discrimination with the CI, the patient also showed improvement in speech perception in noise and sound localization. In our study, all the three subjects with single-sided deafness presented with satisfactory CI performances as well. These findings, though limited, support CIs in patients with traumatic single-sided deafness. In July 2019, the FDA expanded the current CI indications to include patients 5 years and older with single sided deafness and asymmetric hearing loss who have profound SNHL in the ear to be implanted and normal hearing or mild to moderate SNHL in the contralateral ear.<sup>64</sup>

This retrospective case series has several limitations. First, clinical information regarding the date and mechanism of head injury, type of TBF, the CI candidacy evaluation and the CI procedure itself, or postoperative CI performance was unavailable for review in some of the identified cases. Additionally, some of the medical records were from outside institutions from several decades ago and not readily accessible. Second, although this is the largest case series to our knowledge of CI following head injury, our small sample size limits the generalizability of our conclusions. Third, it is important to note that no two TBF are identical, as fracture patterns differ between sides and cases, which could theoretically result in variable injury to neuronal structures and may affect postoperative CI outcomes. Despite these limitations, this article is the first of its kind to study CI following head injury and compare postoperative CNC between those with and without TBF.

In summary, disruption of the otic capsule does not seem to influence CI outcomes in terms of postoperative CNC scores. Cochlear implantation is an effective aural rehabilitation in profound SNHL caused by head injury, both in patients with and without TBF, and even in TBF patients with over a decade of deafness. Future longitudinal studies may help better characterize CI performance over several years in patients with and without TBF, as well as be able to compare outcomes across various CI devices.

## 5 | CONCLUSION

The study is among the largest series examining CI after head injury, and illustrates that CI is an effective method for aural rehabilitation in cases of SNHL after head injury. The presence or absence of TBF does not appear to limit postoperative CNC score.

### CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

### ORCID

Rory J. Lubner  <https://orcid.org/0000-0001-9884-2799>

Renata M. Knoll  <https://orcid.org/0000-0002-5533-4118>

Ryan A. Bartholomew  <https://orcid.org/0000-0002-8310-3544>

Joseph B. Nadol Jr.  <https://orcid.org/0000-0002-4033-3104>

Aaron K. Remenschneider  <https://orcid.org/0000-0003-1974-1880>

Elliott D. Kozin  <https://orcid.org/0000-0002-0305-0682>

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