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Review

Outcomes of Cochlear Implantation in Patients with Temporal Bone Trauma: A Systematic Review and Narrative Synthesis

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Establish outcomes following cochlear implantation (CI) in patients following temporal bone trauma. Systematic review and narrative synthesis. Medline, Pubmed, Embase, Web of Science, Cochrane Collection, and ClinicalTrials.gov. No limits are placed on language or year of publication. The review conducted in accordance with the PRISMA statement. Searches identified 223 abstracts and 64 full texts. Of these, 23 studies met the inclusion criteria reporting outcomes in 77 patients with at least 96 implants. Hearing outcomes were generally good with most patients demonstrating improved audiological and functional outcomes. Complications were reported in 14 cases with 10 of these being major. The methodological quality of included studies was modest, predominantly consisting of case reports and non-controlled case series with small numbers of patients. All studies were OCEBM grade IV. Hearing outcomes following CI in temporal bone trauma are good with useful functional improvement demonstrated in the majority of patients. It appears to be an effective method of aural rehabilitation and should be considered in selected cases following hearing loss due to temporal bone fracture.

KEYWORDS: Cochlear implantation, temporal bone trauma, temporal bone fracture

INTRODUCTION

Background and Epidemiology

Temporal bone fracture is a sign of high energy trauma associated with injury to auditory, vestibular, nervous, and vascular systems. The high energy mechanics required to fracture the temporal bone were traditionally associated with motor vehicle accidents but as the automotive industry continues to improve its safety profile, falls make up an increasingly large proportion of cases. Approximately two-thirds of cases are associated with another skull fracture, more than 3 quarters with intracranial hemorrhage, and approximately 8% associated with mortality.[1]

Diagnosis and Classification

Temporal bone fractures are typically diagnosed through cross-sectional imaging, most commonly computed tomography (CT) head or dedicated temporal bone sequences. Through imaging, temporal bone fractures can be classified in several ways. Traditionally fractures were classified by the directionality of the fracture line; longitudinal, mixed, or transverse to the long axis of the temporal bone. This classification system has been criticized for lack of clinical relevance being a poor predictor for complications such as CSF leak, facial nerve injury, and hearing loss.[2] Consequently, in recent years this has been replaced by a classification reporting fractures in relation to the otic capsule.[3] Most fractures are capsule sparing (80%), however, fractures violating the otic capsule are significantly more likely to demonstrate CSF leak, facial nerve injury, and sensorineural hearing loss.[2,4,5] Both classifications are typically poor at predicting a conductive hearing loss. Q1

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Hearing Loss

Hearing loss in temporal bone fractures may be conductive, sensorineural, or mixed. Conductive loss is seen across all fracture types but most commonly in otic capsule sparing fractures. This may be related to hemotympanum in early stages and ossicular chain disruption in cases of persisting hearing loss.[6] Sensorineural hearing loss may be seen in all fracture types however it is 25 times more likely in otic capsule violating fractures.[4] This may be caused by several mechanisms including disruption of the membranous labyrinth, trauma to the cochlear nerve, interruption of the cochlear blood supply, perilymph fistula, and endolymphatic hydrops.[7-9] Prognosis is often poor and hearing loss may progress over time with cochlear implantation becoming a popular management option.[8]

Considerations for Cochlear Implantation

There are several important considerations that may impact the success of cochlear implantation in patients with temporal bone fractures. Successful implantation requires an intact auditory nerve which may be injured by traction or avulsion in these injuries. As a result, thorough pre-operative assessment with imaging, audiology and sometimes promontory stimulation is key to try to ensure intact and functional auditory nerves.[8] In addition, fracture lines, ossification, and fibrosis found intra-operatively can distort anatomy making access and insertion challenging. As a result, a variety of approaches are often required and failure to fully insert all electrodes has been reported.[10]

Post-operatively, the rate of non-auditory stimulation has been reported to be higher in patients with a temporal bone fracture.[11] This is proposed to be secondary to lower electrical impedance along the fracture lines allowing stimulation of the intratemporal facial nerve.[11]

Finally, due to the forces required to cause temporal bone fracture these injuries are often associated with other significant comorbidities, impaired cognition, behavioral issues, and physical impairment all of which can make post-operative rehabilitation challenging.[8]

Objectives

In this review, we looked at cochlear implant (CI) outcomes in temporal bone fractures, specifically; hearing outcomes and peri/post-operative complications.

Population: Children or adults following temporal bone fracture

Intervention: Cochlear implantation

Comparison: Comparison within the group based on type of anatomical injury present e.g. otic capsule violating versus otic capsule sparing or possible nerve transection

Outcomes: Pre vs post-implantation audiometric outcomes (where pre-implantation outcomes not available inclusion of only post-implantation audiometric outcomes). Complications associated with the peri-operative period in patients receiving cochlear implantation.

MATERIALS AND METHODS

The study protocol was registered in the PROSPERO prospective database of systematic reviews (https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=199335).

Study Inclusion Criteria

Clinical studies of cochlear implantation in patients with temporal bone fractures with hearing outcomes were reported at a minimum of 3 months post-implantation. Diagnosis of temporal bone trauma may be clinical or radiological and of any subtype. Studies of any experimental or observational design in humans were included. Animal studies, and human studies without reports of post-operative audiometric outcomes or where the abstract or full text were unavailable were excluded.

Search Strategy

Two reviewers (ME/KB) independently ran the searches and screened the abstracts. The following databases were searched: Medline, Pubmed, Embase, Web of Science, Cochrane Collection, ClinicalTrials.gov (via Cochrane).

The search terms used were:

#1 "'cochlear implants"
#2 "cochlear implantation"
#3 (cochlear implant*).ti/ab
#4 #1 OR #2 OR #3
#5 Temporal bone fracture*
#6 "Temporal bone trauma"
#7 "Temporal bone injury"
#8 "Head injury"
#9 "Head Trauma"
#10 #5 OR #6 OR #7 OR #8 OR #9
#11 #4 AND #10
No limit was placed on language or year of publication.

Selection of Studies

Two reviewers (ME/KB) independently screened all records by title and abstract identified from the database searches. Studies describing cochlear implantation in patients following temporal bone trauma were assessed against the inclusion and exclusion criteria with any disagreement resolved by discussion with a third reviewer (CM). Studies without accessible abstract or full text after the title/abstract screening were followed up by attempting to contact the study authors. If they remained unavailable the study was excluded. Studies were excluded if they did not report post-intervention audiometric outcomes at a minimum of 3 months post-procedure. Studies, where temporal bone fracture outcomes were grouped with other pathologies, were followed up by contacting the study authors. If data remained indistinguishable the study was excluded. Studies presenting overlapping populations were limited to the largest study sharing data if it is not possible to disambiguate them. Potentially relevant studies identified from the initial searches and abstract screening then underwent full-text screening by the 2 independent reviewers prior to data extraction. Conflicts on the selection were resolved by discussion between the reviewers.

Data Extraction

Data were extracted by the first reviewer (ME) and then checked by a second reviewer (KB). Extracted data were collected in a spreadsheet (Excel, Microsoft Corp, WA, USA).

Risk of Bias Quality Scoring

Two reviewers independently assessed the risk of bias using the Brazzelli risk of bias tool for non-randomized studies.[12] Studies were

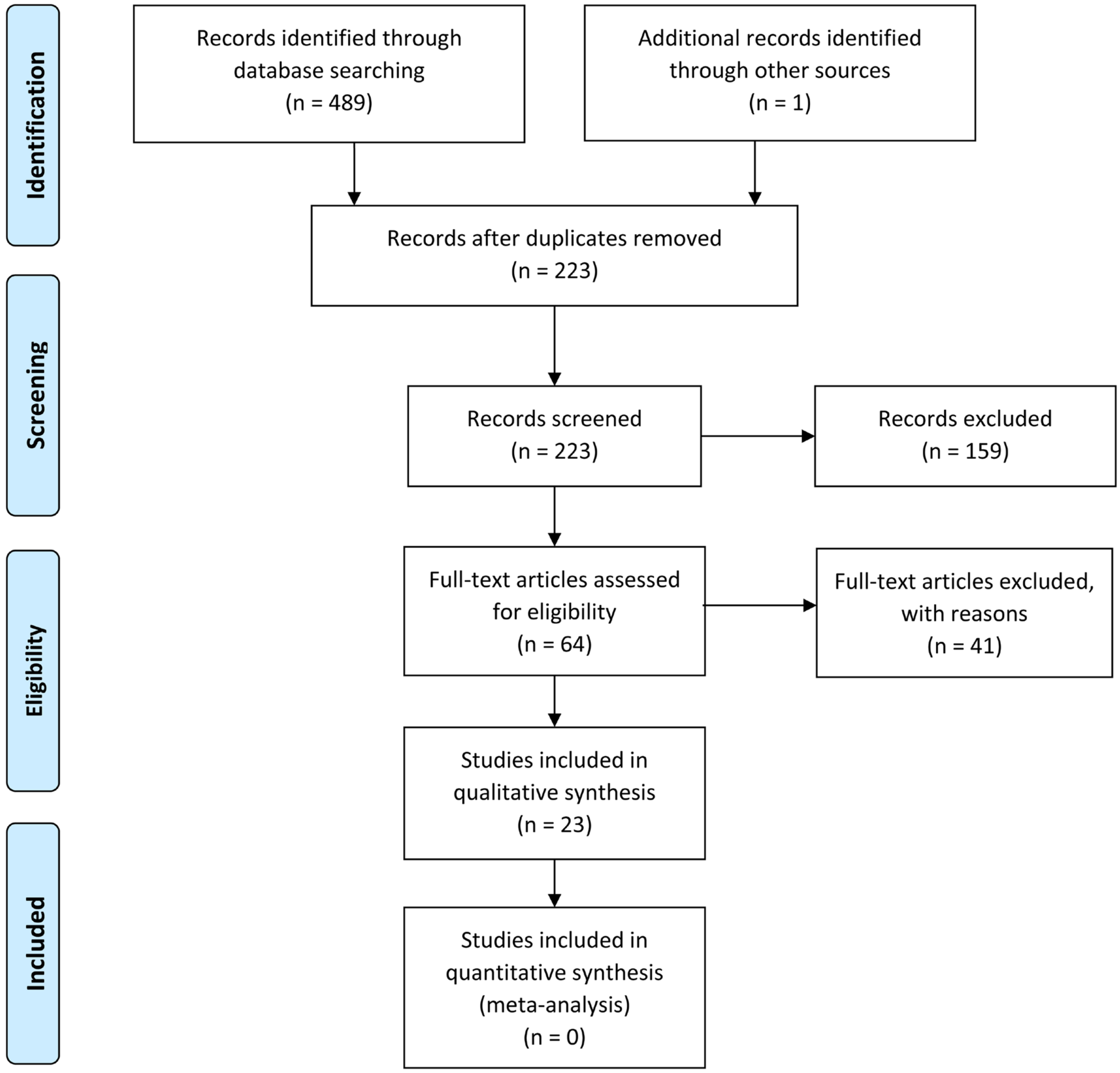

Figure 1. PRISMA flow diagram.

also graded according to the Oxford Centre for Evidence-Based Medicine grading system.[13] Discrepancies between the reviewers were resolved by discussion.

RESULTS

Searches were initially run on (June 8, 2020) and rechecked on (July 6, 2020). A flowsheet detailing study selection according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines is included in Figure 1.

Description of Studies

In this study, 23 studies met the inclusion criteria with a total of 77 patients and 96 implants. There were 11 case series of between 2 and 12 patients and 12 single case reports. All studies were published between 1992 and 2020. Nineteen studies included adult patients only, 3 studies included both adults and children, with 1 case report of a child only. The age at the time of cochlear implantation was highly variable ranging from 8 to 70 years. Duration of deafness was also inconsistent even within studies ranging from 3 weeks to 35 years. The type of cochlear implant used was reported in 18 studies.[8,10,11,14-28]

Radiological assessment of anatomy preoperatively was reported in 20 studies.[8,10,11,14,16-21,23-32] Imaging identified 123 temporal bone fractures: 52 cases were bilateral and 19 unilateral. Varied classification systems were utilized, 54 fractures were otic capsule violating, 3 otic capsules sparing, 31 transverse, and 34 were not classified. At the time of imaging 3 cases reported evidence of labyrinthitis ossificans and 1 of cochlear obliteration.[8,10,14,30] Three studies did not report CT findings, however, fractures were reported to be transverse in 3 cases and not classified in 6 cases.[15,22,32]

Eight patients that underwent cochlear implantation were reported to have cognitive or behavioral issues following head injury.

Full study characteristics are summarised in Table 1.

Quality of Studies

The methodological quality of included studies was modest, predominantly consisting of case reports and non-controlled case series with small numbers of patients. All studies were OCEBM grade IV (Table 1). All studies were retrospective. Heterogeneity of

Table 1. Study Characteristics

Study	Year	Country	Number of Patients	Population	Age At Implantation Average (Range)	Duration of Deafness Months Average (range)	Fracture Laterality	Fracture Classification	Cognitive or Behavioral Issues	Study Type	OCEBM* Grade
Kiefer et al.[14]	2000	Germany	1	Adult	53	12	BL (1)	TV (2)	No	Retrospective Case Report	IV
Trakimas et al.[15]	2019	USA	2	Adult	59 (53-65)	39 (6-72)	BL (2)	TV (3) NS (1)	No	Retrospective Case Series	IV
Lubner et al.[10]	2020	USA	12	Mixed	30.6 (16-65)	104.7 (5-264)	BL (8) UL (4)	CV (13) CS (1) NS (6)	No	Retrospective Case Series	IV
Lachowska et al.[16]	2018	Poland	5	Adult	26.6 (19-37)	3.9 (0.8-6.7)	BL (3) UL (2)	TV (7) NS (1)	No	Retrospective Case Series	IV
Espahbodi et al.[29]	2015	USA	1	Adult	30	17	BL (1)	NS (2)	No	Retrospective Case Report	IV
Medina et al.[30]	2014	Italy	9	Adult	51 (19-62)	NA	BL (6) UL (3)	CV (13) CS (2)	No	Retrospective Case Series	IV
Vermeire et al.[17]	2012	Netherlands	4	Adult	31.75 (21-46)	NA	BL (4)	NS (8)	No	Retrospective Case Series	IV
Greenberg et al.[8]	2011	Canada	8	Adult	45.8 (29-64)	11.4 (1-35)	BL (4) UL (4)	TV (12)	Yes (3)	Retrospective Case Series	IV
Serin et al.[18]	2010	Turkey	5	Mixed	37.4 (12-46)	11 (6-14) 1 case NS	BL (3) UL (1) NS (1)	CV (7) NS (1)	No	Retrospective Case Series	IV
Hagr.[19]	2011	Saudi Arabia	5	Adult	35 (25-54)	16 (4-36)	BL (4) UL (1)	CV (7) TV (2)	Yes (1)	Retrospective Case Series	IV
Simons et al.[20]	2005	USA	1	Adult	25	12	BL (1)	CV (2)	No	Retrospective Case Report	IV
Plontke et al.[21]	2013	Germany	1	Children	8	2	UL (1)	CV (1)	No	Retrospective Case Report	IV
Camilleri et al.[11]	1999	UK	7	Mixed	44 (13-69)	112 (11-420)	BL (6) UL (1)	NS (13)	No	Retrospective Case Series	IV
Bendet et al.[22]	1998	Switzerland	1	Adult	37	24	BL (1)	NS (2)	Yes (1)	Retrospective Case Report	IV
Shin et al.[23]	2008	Korea	1	Adult	65	3	BL (1)	CV (2)	Yes (1)	Retrospective Case Report	IV
Zanetti et al.[24]	2010	Italy	1	Adult	41	5	BL (1)	CV (2)	No	Retrospective Case Report	IV
Chung et al.[31]	2011	Korea	1	Adult	44	1.75	BL (1)	CV (2)	No	Retrospective Case Report	IV
Glaas et al.[25]	2019	Germany	5	Adult	43.8 (31-50)	33.6 (2-139)	BL (5)	TV (8) NS (2)	No	Retrospective Case Series	IV
Jeon et al.[26]	2014	Korea	1	Adult	33	24	BL (1)	CV (2)	No	Retrospective Case Report	IV
Moore & Cheshire[33]	1999	UK	3	Adult	52.3 (29-64)	80 (24-240)	NS (3)	NS (3)	Yes (1)	Retrospective Case Series	IV
Coligado et al.[32]	1993	USA	1	Adult	26	23	UL (1)	CV (1)	Yes (1)	Retrospective Case Report	IV
Maas et al.[27]	1996	UK	1	Adult	70	24	UL (1)	NS (1)	No	Retrospective Case Report	IV
Marsh et al.[28]	1992	USA	1	Adult	20	21	BL (1)	CV (2)	No	Retrospective Case Report	IV

NS, not specified; UL, unilateral; BL, bilateral; TV, transverse; CV, otic capsule violating.

audiological outcomes precluded a meta-analysis. There were also limitations in reporting of implant used and surgical technique.

Audiological Outcomes

Hearing outcomes were generally good across all studies; however, reporting was heterogenous both in terms of assessment method and follow-up duration. The shortest duration of follow-up was reported to be 4 months and the longest follow-up was 96 months. A total of 33 different audiological outcome measures were used across the studies with inconsistent reporting of pre and post-operative outcomes. A pre-implant hearing was reported using pure tone audiology (PTA) in 20 studies. All cases were reported to have deficits in the severe to profound range.

PTA was the most frequently used outcome measure being reported in 11 studies. Average pure tone thresholds post-CI were reported in 10 studies, ranging from 20 to 45 dB. One study reported only that post-operative thresholds were in the normal to mild hearing loss range.[29]

All 23 studies assessed speech perception using various methods. Three studies used the Freiburg test to assess post-operative speech perception. A case report by Plontke et al. also used this pre-operatively demonstrating an improvement in recognition of monosyllabic words from 0% to 100%.[21] Bamford–Kowal–Bench (BKB) scores were also used to assess speech perception in 3 studies. Maas et al. and Camilleri et al. also used BKB scores preoperatively both demonstrating improvement.[11,27] Other outcomes assessing speech perception included; Central Institute for the Deaf sentences, Innsbruck sentences, Gottenburg sentences, Iowa sentences, City University of New York Sentences, Hearing in Noise Test, Phoneme tests, Spondee tests, Word Recognition Score, Sentence Recognition Score, University College hospital test of environmental sound recognition score, GASP-K score, 5 Vowel test, and the Nederlandse Vereniging Voor Audiologie monosyllabic word test.

Only 1 study performed statistical analysis between pre and post-implant hearing outcomes. Lachowska et al. found that there was a statistically significant improvement in both PTA and speech recognition in their series.[16]

Several studies utilized descriptive analysis of post-implant function. Four studies reported an understanding conversation with family, 6 studies reported telephone use and 6 studies reported regular implant use. Zanetti et al. utilized the abbreviated profile for hearing aid benefit (APHAB) to demonstrate good patient satisfaction post-implant with global scores of 9/10.[24] Additionally, Vermeire et al. assessed post-operative function and satisfaction with the Hearing Handicap Inventory for Adults questionnaire with average scores of 51.5/100 (range 26-70).[17] Moore and Cheshire utilised Depress F/Q scores and the Revised Denver communication scale to assess handicap and depression. These identified similar post-implant outcomes to non-head injured patients with the exception of 1 case with cognitive/behavioral impairments.[33]

Overall, trends demonstrated patients experiencing improved hearing outcomes and functional benefit following cochlear implantation regardless of the measures used although this was rarely reported with statistical analysis. Out of the 96 implants, only 3 cases required further intervention due to poor hearing outcomes, with 2 requiring reimplantation and 1 eventually having an auditory brainstem implant.[10,15,18,33] Audiological outcomes are summarised in Table 2.

Surgical Outcomes

Details on surgical procedures and outcomes can be found in Table 3. Fourteen studies reported no surgical complications. In the remaining 9 studies there were 14 reported complications, 10 were major (requiring inpatient treatment or further procedure), and 4 minor. Three cases reported poor initial or deteriorating hearing outcomes requiring the further procedure.[10,15,18,33] Six patients experienced facial nerve stimulation (FNS), 3 of whom required reimplantation.[10,11,25,27,29] There were 3 cases of post-operative infection with 2 patients developing meningitis and 1 requiring implant removal due to infection.[22,28,31] Other complications included 1 case of wound dehiscence and 1 patient with mild facial nerve palsy managed successfully with steroids.[10,18]

Out of 96 implants 8 were only partially inserted due to resistance, and the extent of insertion was not specified in 11 cases. Partial insertion did not correlate with CT findings of cochlear ossification however, 3 of the 4 studies reporting partial insertion identified distorted anatomy intra-operatively.[10,11,18]

DISCUSSION

This systematic review and narrative synthesis reports on outcomes of cochlear implantation in patients with profound sensorineural hearing loss following temporal bone fractures. To the authors' knowledge, this is the first dedicated systematic review on this topic.

Most studies reported good audiological outcomes, with the majority of patients receiving the benefit. All studies reported speech perception and most reported pure-tone audiograms post-implantation. In terms of long-term outcomes, 2 cases were reported with declining cochlear implant function over time requiring re-implantation. However, 5 further papers were identified which did not specify follow-up period or reported follow-up less than 3 months. All 5 reported good audiological and speech perception outcomes described good audiological outcomes.[34-38]

Four studies were able to compare hearing outcomes to non-temporal bone fracture cochlear implant groups. Lubner et al. compared speech perception in temporal bone fracture patients versus other head injury patients. This showed no statistically significant difference between Consonant Nucleus Consonant scores.[10] Similarly, Coligado et al. described comparable speech perception scores following cochlear implant in a case of bilateral temporal bone fracture when compared to 19 other non-cochlear implant recipients.[32] Moore and Cheshire reported mixed results when compared to non-head injured cochlear implant recipients. In 2 cases BKB and functional scores were comparable, however, 1 patient with cognitive and behavioral issues following head injury experienced less successful auditory rehabilitation becoming depressed and ultimately stopped using their implant.[33]

Although cognitive impairment has been reported to complicate auditory rehabilitation, only 2 of the 8 cases reporting such cognitive or behavioral issues described poor outcomes.[8,19,22,23,32,33] The low number of negative outcomes is likely due to stringent screening and appropriate patient selection as described by Greenberg et al.[8] This

Table 2. Hearing Outcomes

	Pre-operative Data	Post-operative Data	Overall Benefit (Subjective Assessment)	Average Follow-up
Kiefer et al.[14]	**Not reported**	**Speech perception scores:** Freiburg Test- numbers 100%, monosyllables 43%, vowels 56%, consonants 70%, Innsbruck sentences- 98%, Göttingen sentences- 75%	Successful outcomes with scala vestibuli insertion in patients with obstructed scala tympani. Comparable to outcomes in other post-lingually deafened adults	48 m
Trakimas et al.[15]	**Pure-tone audiometry:** Patient 1- No Response Patient 2- No Response	**Speech perception scores:** Patient 1- Monosyllable words 30% Patient 2- CID Sentences 4%	Poor to moderate improvement demonstrated with reimplantation necessary in patient 2	19 m
Lubner et al.[10]	**Pure-tone audiometry:** Group A (Temporal Bone Fracture)- 101 dB Right (1 No response, 2 unknown), 91 dB Left (1 No Response, 2 Unknown) Group B (Head Injury without fracture)- 85 dB Right (1 No response), 69 dB (2 no response)	**Speech perception scores:** Group A- CNC: Words- 71% (26-92%), Phoneme 85% (70-97%) (1 case excluded as no neural response on testing & later underwent ABI) Group B- CNC: Word 66% (22-90%), Phoneme 81.5% (53-97%) (2 cases only tested Monosyllable words 35.4%, 1 case only took AZBio in Quiet test 60%) No significant difference between CNC scores between 2 groups (p=0.639) No significant correlation between duration of deafness & CNC score (r = 0.033, p=0.908)	CI is an effective method of auditory rehabilitation in patients with head injury. No difference between patients with or without fractures	77.5 m
Lachowska et al.[16]	**Pure-tone audiometry:** PTA- Mean 98 (1 No Response) **Speech perception scores:** One Syllable Word Recognition Score: 0% Multisyllable Word Recognition Score: 0% Sentence Recognition Score: 0%	**Pure-tone audiometry:** PTA- Mean 30 dB **Speech perception scores:** One Syllable Word Recognition Score: Mean 83.3%, Median 80% (60-100%) Multisyllable Word Recognition Score: Mean 98.3%, Median 100% (90-100%) Sentence Recognition Score: Mean 98.3%, Median 100% (90-100%) Wilcoxon signed-rank test and Friedman repeated measures analysis of variance by ranks demonstrated significant improvement over time in PTA (p=<0.05) & speech recognition score (p=<0.05) **Other** All Regular users of implant & able to have conversation, 5 able to use telephone	CI is an effective treatment method for patients deafened following blunt head trauma.	12 m
Espahbodi et al.[29]	**Pure-tone audiometry:** PTA- Bilateral profound SNHL	**Pure-tone audiometry:** PTA thresholds in the normal to mild hearing loss range **Speech perception scores:** HINT sentences (Quiet, in Spanish) scores: 97% right, 98% left, 99% bilaterally	Successful auditory rehabilitation and management of FNS following CI with adjustments to programming	5 m
Medina et al.[30]	**Pure-tone audiometry:** PTA- 5 cases bilateral anacoustic, 3 cases profound bilateral SNHL, 1 case left anacoustic right profound SNHL	**Speech perception scores:** Vowel Identification: Mean 98.75% (90-100%) (1 case not reported) Bisyllabic Word Recognition: Mean 76.1% (30-100%) Sentence Recognition: Mean 89.7% (69-100%) 1xN Common phrases comprehension 88.1% (70-100) (1 case not reported) **Other** 2 patients able to use telephone	CI after temporal bone fractures has proved to have excellent audiometric results.	53.4 m

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	Pre-operative Data	Post-operative Data	Overall Benefit (Subjective Assessment)	Average Follow-up
Vermeire et al.[17]	**Pure-tone audiometry:** PTA- Bilateral profound SNHL in all 4 cases	**Pure-tone Audiometry** Mean implant aided audiometry 28 dB **Speech perception scores:** NVA monosyllabic word test: Mean 62.2% (24-95%) Plomp sentences: Mean 58.3% (10-95%) Signal to noise ratio: Mean 17.8 dB (5.8-30) Antwerpen-Nijmegen battery (minimal audition capabilities battery) Consonant test: 52.8% (31-85) Short vowel test: 70% (42-100) Long vowel test: 84% (58-98) **Other** HHIA questionnaire: Mean 51.5/100 (26-70)	CI in patients suffering from profound sensorineural hearing losses secondary to TB fractures can be an effective tool for rehabilitation.	51.5 m
Greenberg et al.[8]	**Pure-tone audiometry:** PTA- Mean: 114.8 dB Right, 119.4 dB Left	**Speech perception scores:** CUNY Sentence score: Mean 65.2% (16-100) 2 not formally tested as not English speaking- 1 reportable to use the telephone	CI outcomes in head injury are comparable to other CI populations. Concomitant brain injury can complicate rehabilitation	12 m
Serin et al.[18]	**Pure-tone audiometry:** PTA- Bilateral profound SNHL in all 5 cases	**Pure-tone audiometry:** PTA- Mean 43 dB **Speech perception scores:** Closed-set initial phoneme recognition test: Mean 99.2% (96-100%) Closed-set final phoneme recognition test: Mean 100% Open-set 3-syllabic word identification test: Mean 96.8% (84-100%) Open sentence test: Mean 94.4% (80-100%)	CI is an effective aural rehabilitation in profound SNHL caused by temporal bone trauma.	43.2 m
Hagr.[19]	**Pure-tone audiometry:** PTA- Bilateral profound SNHL in all 5 cases	**Pure-tone audiometry:** PTA- Mean 30 dB (30 dB for patient 1, 2 and 5. Not reported patient and 4) **Other:** All regular implant users Patient 1 able to use telephone Reported understanding of conversation with family- 70% patient 1, 90% patient 2, 40% patient 3 and 70% patient 5. Average 67.5%	Recommend bilateral CI in patients with hearing loss due to bilateral fractured inner ears.	30 m
Simons et al.[20]	**Pure-tone audiometry:** PTA- Bilateral profound SNHL **Speech Recognition**: Iowa sentence test scores 0/88 CID sentence score 1/200	**Speech Recognition:** Iowa sentence test scores 72/88 CID sentence score 174/200 **Other:** Able to use telephone	Successful aural rehabilitation after CI in a case of SNHL following temporal bone fracture	6 m
Plontke et al.[21]	**Pure-tone audiometry:** PTA- bilateral anacousis **Speech perception scores:** Freiburg test- Multisyllabic numbers 0%	**Speech perception scores:** Freiburg test- multisyllabic numbers 100% Monosyllabic numbers 90% Signal to noise ratio in normal levels using Oldenbourg Sentence test Reduction in angle detection error	CI in an acutely deafened child with a temporal bone fracture can lead to good speech discrimination, speech perception in noise and sound localisation	6 m
Camilleri et al.[11]	**Pure-tone audiometry:** PTA- Mean 96.6 dB (90-106) **Speech perception scores:** BKB: Mean 21.7% (0-74%) VCV: Mean 32.2% (25-37.5%)- 1 case not assessed	**Pure-tone audiometry:** CI assisted PTA: Mean 45 dB (40-50) **Speech perception scores:** BKB: Mean 73.4% (44-100%) VCV: Mean 62.7% (31.25-89.5%)- 1 case not assessed Environmental sound recognition: Mean 12/20 (5.5-17.5/20) **Other:** 6 patients became daily users	CI following temporal bone fracture has good audiometric and psychoacoustic results. Comparing favorably with other etiologies. Although there is a higher rate of FNS	9 m

(Continued)

	Pre-operative Data	Post-operative Data	Overall Benefit (Subjective Assessment)	Average Follow-up
Bendet et al.[22]	**Not Reported**	**Speech perception scores:** 5-Vowel Test: 80% **Other:** Able to lip read. Understands close family. Functioning limited by vestibular function & neurological sequelae.	Subtotal petrosectomy can allow safe implantation. Improved hearing outcome but limited by other sequelae.	12 m
Shin et al.[23]	**Pure-tone audiometry:** PTA- Slight low frequency residual hearing on right only	**Pure-tone audiometry:** CI assisted PTA: Mean 30 dB **Other:** Understands 70% of the usual conversation with family Regular implant user	CI, with careful planning in temporal bone fractures, is a very effective method for aural rehabilitation.	18 m
Zanetti et al.[24]	**Pure- tone audiometry:** PTA- no response right, 120 dB left	**Pure-tone audiometry:** CI assisted PTA: 20 dB **Speech perception scores:** Speech tracking: 47 words/min Open Set Word recognition scores: 100% Open Set Sentences recognition scores: 100 **Other:** APHAB: 9/10 global score Able to use telephone	CI in temporal bone fractures is feasible. Success in this case likely due to early intervention	18 m
Chung et al.[31]	**Pure-tone audiometry** PTA- no response at maximum thresholds	**Pure-tone audiometry:** CI assisted PTA: 25 dB **Speech perception scores:** Open Set word perception test- Monosyllabic 100%, Bisyllabic 100%	Bilateral cochlear implantation in patients with temporal bone fractures can be a very effective tool for rehabilitation.	14 m
Glaas et al.[25]	**Not Reported**	**Speech Perception scores:** Freiburg test- Monosyllabic: Mean 67% (24-84%)	CI in patients with SNHL after temporal bone fracture is a good therapeutic option. Timely intervention is recommended	12 m
Jeon et al.[26]	**Pure-tone audiometry:** PTA- Bilateral profound SNHL	**Pure-tone audiometry:** CI aided PTA- 40 dB **Speech Perception Scores:** GASP-K: 100%	CI can be a good auditory management option in patients with profound deafness following bilateral transverse temporal bone fractures,	84 m
Moore & Cheshire[33]	**Pure-tone audiometry:** PTA- Bilateral profound SNHL in all 3 cases	**Speech Perception Scores:** BKB: Fracture group Mean 68.3% (43-92%) Non-Head Injured mean: 90% UCH test of environmental sound recognition: Fracture group Mean 54% (32-70) Non-Head Injured mean: 58% Connected Discourse Tracking- Fracture group Mean 55 words/min (49-62) Non-Head Injured mean: 66 words/min **Other:** Depress F: Fracture group Mean 3 (2-5), Non-Head Injured mean: 3 Depress Q: Fracture group Mean 4 (0-11), Non-Head Injured mean: 2.2 REVNED score: Fracture group Mean 5.0 (3.4-8), Non-Head Injured mean: 5.8 2 daily users of implants	Post CI performance was comparable to patients without fractures in fracture patients without cognitive deficit. Important to consider cognitive factors when planning CI	18 m

	Pre-operative Data	Post-operative Data	Overall Benefit (Subjective Assessment)	Average Follow-up
Coligado et al.[32]	**Pure-tone audiometry:** PTA- Right 82, Left no response **Speech Perception Scores:** **Closed set** 4-Choice Spondee: Patient 60%, Other CI average 60% Vowel recognition: Patient 33%, Other CI average 27% **Open set** NU-6 Word: Patient 12%, Other CI average 2% NU-6 Phoneme: Patient 34%, Other CI average 9% CID Sentences: Patient 6%, Other CI average 16% **Speechreading** CID Sentences: (SR+HA): Patient 23%, Other CI average 61%	**Pure-tone audiometry:** PTA- 29 dB **Speech Perception Scores:** **Closed set** 4-Choice Spondee: Patient 95%, Other CI average 95% Vowel recognition: Patient 82%, Other CI average 71% **Open set** NU-6 Word: Patient 30%, Other CI average 20% NU-6 Phoneme: Patient 51%, Other CI average 45% CID Sentences: Patient 66%, Other CI average 43% **Speechreading** CID Sentences: (SR+CI): Patient 82%, Other CI average 88% **Other:** Daily user of implant. Demonstrated functional gains after implantation	CI showed improvement in speech recognition and functional skills. CI should be considered in patients with traumatic SNHL with relatively intact cognitive skills.	14 m
Maas et al.[27]	**Pure-tone audiometry:** PTA- Bilateral anacousis **Speech Perception Scores:** BKB: 0%	**Speech Perception Scores:** BKB 90%	CI allowed good speech perception. Explantation and contralateral reimplantation should be considered in cases of FNS	9 m
Marsh et al.[28]	**Pure-tone audiometry:** PTA- Right 81.6 dB Left 77.5 **Speech Perception Scores:** **Closed set** Four-Choice Spondee: 35.0% Vowel-Iowa: 4.8% Medial consonant-Iowa: 7.0% **Open set** CID sentences: 0.5% Monosyllabic words (NU-6) Words: 0% Phonemes: 5.3%	**Speech Reception:** Speech Tracking: 25 words/min Vowel Confusion Study: Closed Set (LR+CI): 97% Open Set common sentence recognition: 78%	Significant improvement in speech perception and tracking post CI	4 m

APHAB, abbreviated profile for hearing aid benefit; BKB, Bench-Kowal-Bamford Sentences; CI, Cochlear Implant; CID, Central Institute for the Deaf Sentences; CNC, Consonant Nucleus Consonant; CUNY, City University of New York Sentences; FNS, Facial Nerve Stimulations; GASP-K, Glendonald Auditory Screening Procedure-Korean; HA, Hearing Aid; HHIA, Hearing Handicap Inventory for Adults; HINT, Hearing in Noise Test; LR, Lip Reading; NVA, Nederlandse Vereniging Voor Audiologie; PTA, Pure Tone Audiometry; REVNED, Revised Denver communication scale; SNHL, sensorineural hearing loss; SR, Speech Reading; VCV, Vowel Consonant Vowel score.

Table 3. Surgical Outcomes

Study	Number of Implants	Type of Implant	Implant Laterality	Insertion	Intraoperative Findings	Operative Complications
Kiefer et al.[14]	1	CI 22 min (1)	UL (1)	C (1)	Scala tympani subtotally ossified and fibrotic (1)	Nil
Trakimas et al.[15]	3	CI 22 min (2) House Single Channel (1)	UL (3)	C (3)	Nil	Re-implanted at 5 years reduced performance (1)
Lubner et al.[10]	16	Cochlear nucleus 22 (1) Cochlear Nucleus 24 (3) Med-el Flex 28 (1) Cochlear CI512 (1) Cochlear CI532 (1) Advanced Bionics (8) Ineraid (1) HiRes 90K (1)	UL (8) BL (4)	C (12) P (4)	Cochlear ossification (1) Microfracture RW (3) Fibrosis Basal turn (2) RW adhesion (1)	FNS (1) Wound dehiscence (1) ABI due to poor performance (1)
Lachowska et al.[16]	6	Nucleus Cochlear (4), Digisonic Neurelec (2)	UL (4) BL (1)	C (6)	Nil	Nil
Espahbodi et al.[29]	2	NS	BL (1)	C (2)	Nil	FNS (1)
Medina et al.[30]	12	NS	UL (6) BL (3)	C (12)	Nil	Meningitis (1)
Vermeire et al.[17]	4	Med-el C40+ (2) Nucleus CI22 (1) Laura (1)	UL (4)	C (4)	Nil	Nil
Greenberg et al.[8]	8	Nucleus 22M (5) ABC 90K (3)	UL (8)	C (8)	Nil	Nil
Serin et al.[18]	6	Medel Pulsar (3) Nucleus 24M (1) Med-el C40+ (2)	UL (6)	C (5) P (1)	Free blood in cochlea (2) OW & RW not identified (1) Partial Ossification Cochlea (1)	Facial Palsy (1) Re-implanted at 2 years reduced performance (1)
Hagr.[19]	6	Nucleus Freedom CI24RE (6)	UL (4) BL (1)	C (6)	Fracture crossing promontory & RW (1), Fibrous tissue on RW (1)	Nil
Simons et al.[20]	1	Nucleus 22 (1)	UL (1)	C (1)	Nil	Nil
Plontke et al.[21]	1	Cochlear CI512 (1)	UL (1)	C (1)	Nil	Nil
Camilleri et al.[11]	9	Nucleus 22 (8) Ineraid (6)	UL (9)	C (7) P (2)	Partially obliterated the basal turn (2) Total cochlear obliteration (1)	Re-implanted due to FNS (2)
Bendet et al.[22]	2	Nucleus CI (1)	UL (2)	NS (2)	Fracture line over promontory to RW (1)	Removed due to infection (1)
Shin et al.[23]	1	HiRes 90K (1)	UL (1)	P (1)	Nil	Nil
Zanetti et al.[24]	2	Nucleus Contour Advance (2)	BL (1)	C (2)	Nil	Nil
Chung et al.[31]	2	NS	BL (1)	C (2)	Fracture through promontory & Fibrous tissue on RW (1)	Nil
Glaas et al.[25]	6	Cochlear CI512 (4) Freedom (1) HiRes90K (1)	UL (4) BL (1)	NS (6)	Nil	FNS (1)
Jeon et al.[26]	1	Nucleus 24M (1)	UL (1)	C (1)	Fibrous band & fractured bony fragment in tympanic cavity (1)	Nil
Moore & Cheshire[33]	3	NS	UL (3)	NS (3)	Nil	Nil
Coligado et al.[32]	1	NS	UL (1)	C (1)	Nil	Nil
Maas et al.[27]	2	Nucleus 22 (2)	UL (2)	C (2)	New bone at basal turn (1)	Re-implanted due to FNS (1)
Marsh et al.[28]	1	Nucleus 22 (1)	UL (1)	C (1)	Nil	Meningitis (1)

BL, Bilateral; NS, Not Specified; UL, Unilateral; C, Complete insertion; P, Partial insertion; OW, Oval Window; RW, Round Window; ABI, Auditory brainstem implant; FNS, Facial Nerve Stimulation.

area is complex and no studies clearly described criteria for the selection or exclusion of such patients. However, it would seem that these patients have been screened out given the severity of head injury required to cause bilateral temporal bone fracture and low numbers of cognitively impaired patients being implanted. As a result, it is recommended that thorough assessment is undertaken in these patients to ensure that they are likely to benefit from implantation and engage with the rehabilitation process.

Nineteen studies reported pre-operative imaging findings. In addition to the fractures described previously, CT and MRI showed only 3 cases of labyrinthitis ossificans and 2 cases of obliteration/obstructed cochlea.[8,10,14,30] However, this only correlated in difficult/partial insertion of electrodes in 1 study.[10] Reporting of intra-operative findings was inconsistent, and imaging did not consistently correlate with anatomical findings at surgery. Three studies reporting no ossification/obliteration on imaging but encountered this intraoperatively with difficult/partial insertion of electrodes in 3 cases.[11,18,27] It is well recognized that distorted anatomy can make cochlear implantation difficult either from fractures obstructing the cochlea, healing via fibrosis, or from labyrinthitis ossificans.[37] As in other causes of labyrinthitis ossificans implantation should be considered as an "emergency."[39] The studies presented to highlight that pre-operative imaging with CT or MRI can be useful in identifying these changes, however, it is important to be aware that imaging can be falsely reassuring.

Cochlear ossification not only poses a challenge for insertion of implants but may influence audiological outcomes. Four studies report 4 cases of cochlear ossification with variable hearing outcomes.[8,10,14,18] Lubner et al and Kiefer et al both report good speech perception scores post-implantation in cases with cochlear ossification.[10,14] However, Greenburg et al found the worst-performing implant in their series showed evidence of ossification on CT and similarly, Serin et al found that their patient with cochlear ossification required reimplantation due to poor hearing outcomes.[8,18] Poorer outcomes have been reported in cochlear ossification post-meningitis and as such warrant early intervention.[40] This may also be the case in temporal bone fracture patients. However, the current literature does not provide sufficient data to support the optimal timing of intervention.

The use of promontory stimulation testing (PST) in the workup for cochlear implantation is somewhat controversial. Positive stimulation has been reported to correlate with better speech perception post-implantation.[41,42] However, there is conflicting evidence in the wider literature suggesting positive PST does not always correlate with good outcomes and that some patients with a negative PST will still have a functioning auditory nerve and may benefit from implantation.[41,43] PST was reported in 19 patients across 8 studies, all of whom reported positive responses.[8,10,17,18,20,24,26,32] In this review no patients were identified who were implanted without positive response to PST. In keeping with existing literature, findings identified some discord between positive response to PST and hearing outcomes. One patient presented by Serin et al. had positive PST but developed deteriorating CI function over the 2 years following implantation.[18] Furthermore, 2 of the lowest-performing patients presented by Greenburg et al. were found to have a positive response to PST.[8] Despite these cases most patients with temporal bone fracture and positive PST had good post-implant outcomes. As a result, PST may be a useful adjunct in the pre-operative workup of these patients although it should be used as an approximate guide only, and in combination with audiology and imaging to assess auditory nerve continuity.

The rate of complications across the reported studies was reported to be high, at 14.5%, with most complications being major requiring inpatient treatment or further surgery. Major complications included implant infection, meningitis, wound dehiscence, and implant failure. The most frequently observed complication across the studies was FNS in 6%. Half of these cases were considered minor and managed successfully by altering programming. However, 3 cases required reimplantation on the contralateral side.[11,27] The rate of FNS in patients is reported to be high, hypothetically because there is reduced electrical impedance along fracture lines allowing stimulation of the facial nerve.[8] The reported rates in the literature for CI patients are highly variable from 0.9% to 14%.[44-49] From the studies presented, temporal bone fracture patients undergoing CI are a high-risk group for FNS. As half of the patients that develop FNS require reimplantation, it should be discussed in pre-operative counseling.

The small sample sizes of reported cases raise questions about the validity of pooled results. This would best be addressed by the adoption of large-scale mandatory registries of implantation recipients and their outcomes. Such registries are not currently in use but the increase of electronic patient records and increased interest in outcome measures may drive implementation. Whilst a number of challenges exist with the implementation of national registries, such as oversight, funding, and legal implications, there are trends towards the development of these databases for cochlear implantation.[50,51] Furthermore, a standardized approach to reporting of outcomes, including pre and postoperative audiology, would facilitate the synthesis of a wider pool of data and provide opportunities to more accurately assess outcomes on a larger scale.

CONCLUSION

Hearing outcomes following CI in patients with temporal bone fractures are generally good with the majority of patients experiencing a benefit, both in terms of pure tone audiology and speech perception. Pre-operative imaging is recommended to assess the extent of fracture and continuity of the vestibulocochlear nerve supported with audiological assessment and promontory stimulation. In addition, a thorough assessment of patient's motivation, physical and cognitive functioning are vital in selecting patients who are most likely to engage and benefit from aural rehabilitation with a cochlear implant however, no set criteria are currently available. Significant complications such as the risk of; infection, implant failure, facial nerve palsy, and FNS should be discussed with the patient and family during pre-operative counseling. Overall CI appears to be an effective method of auditory rehabilitation and should be considered in appropriately selected cases with profound hearing loss following a temporal bone fracture.

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