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# Tinnitus suppression in a prospective cohort of 45 cochlear implant recipients: occurrence, degree and correlates

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## Abstract

**Objective** To determine tinnitus prevalence and severity in a cohort of unselected first-time cochlear implant (CI) recipients whose primary motive for CI was sensorineural hearing loss (SNHL), and to evaluate the effect of CI on tinnitus after cochlear implantation.

**Methods** Prospective longitudinal study of 45 adult CI recipients with moderate to profound SNHL. Patients completed the Danish version of the Tinnitus Handicap Inventory (THI) and a visual analogue scale (VAS) for tinnitus burden before implantation, 4 months after implantation and 14 months after implantation.

**Results** The study included 45 patients, of which 29 (64%) had pre-implant tinnitus. Median THI score (IQR) significantly decreased from 20 (34) to 12 (24) at first follow-up ($p < 0.05$) and to 6 points (17) at second follow-up ($p < 0.001$). Median VAS (IQR) for tinnitus burden decreased from 33 (62) to 17 (40; $p = 0.228$) and 12 (27, $p < 0.05$) at the first and second follow-ups, respectively. Tinnitus was totally suppressed in 19% of patients, improved in 48%, remained unchanged in 19% and worsened in 6%. 2 patients reported new tinnitus. At the second follow-up, 74% of patients had slight or no tinnitus handicap, 16% had mild handicaps, 6% had moderate handicaps, and 3% had severe handicaps. High pre-implant THI and VAS scores correlated with greater decrease in THI scores over time.

**Conclusion** 64% of the patients with SNHL had pre-implant tinnitus, which was decreased 4 and 14 months after implantation. Overall, 68% of patients with tinnitus improved their tinnitus handicap after CI. Patients with higher THI and VAS scores had a larger decline and the highest benefits in terms of tinnitus handicap improvement. The study findings demonstrate that the majority of patients with moderate to profound SNHL eligible for cochlear implantation benefit from complete or partial tinnitus suppression and improved quality of life after implantation.

**Keywords** Cochlear implant · Tinnitus · Treatment · Hearing rehabilitation · Hearing loss

## Abbreviations

| | |
|---|---|
| CI | Cochlear implant |
| dB HL | Decibel hearing level |
| HA | Hearing aid |
| NCIQ | Nijmegen cochlear implant questionnaire |
| PTA6 | Pure-tone audiometry average for six frequencies |
| SNHL | Sensorineural hearing loss |
| SRS | Speech reception score |
| SSQ-12 | Speech, Spatial, and Qualities of Hearing Scale |
| THI | Tinnitus Handicap Inventory |

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## Introduction

Tinnitus is frequently observed in patients with moderate to profound sensorineural hearing loss (SNHL) [1], and it causes difficulties in concentration, sleep, anxiety and depression [2–4], and overall quality of life [5–8]. The prevalence of tinnitus, which affects 65 million adults in Europe with 4 million experiencing severe symptoms, is influenced by patient age and the degree of hearing loss. [9–11] Patients with hearing loss are three times more likely to experience tinnitus than those with normal hearing [12].

Cochlear implants (CI) are the preferred treatment for moderate to profound SNHL when hearing aids (HA) are

ineffective, with the potential to reduce tinnitus in both unilateral and bilateral SNHL patients [13–15]. In one study, 80% of candidates with bilateral profound SNHL experienced pre-implant tinnitus, and after implantation, 86% of patients reported a decrease in tinnitus. [14]. Despite various hypotheses such as auditory masking, surgical effects, central auditory plasticity [16], and intra-cochlear electrical stimulation, the mechanisms by which CI alleviate or suppress tinnitus remain unknown. [13, 14, 17, 18]. Earlier studies found that cochlear implants suppresses tinnitus, but the factors that influence this suppression differ across studies [9, 17, 19–23].

In this study, we aim to evaluate the prevalence and severity of tinnitus in patients with sensorineural hearing loss who are eligible for cochlear implantation and to investigate the impact of cochlear implantation on tinnitus. We use a tinnitus handicap questionnaire to investigate whether CI suppresses tinnitus handicap and how tinnitus suppression relates to speech reception and patient-reported quality of life.

## Materials and methods

Adult patients with SNHL who meet the Danish national candidacy criteria for CI were included in this prospective longitudinal study, regardless of whether they had tinnitus [24]. Patients under the age of 18, those who were unable or unwilling to participate in the study, and those who had bilateral cochlear implantation were excluded. If a patient received a second cochlear implant later, the data collected up until that point was included in the analysis.

### Cochlear implantation

Following mastoidectomy and posterior tympanotomy to reach cochlea, we used the round window surgical technique to implant the electrode. In Denmark, the brand of implant device is chosen in collaboration between the patient and the speech and language pathologist, but the implant electrode is generally chosen by the surgeon. Four different surgeons conducted CI, and they had all performed over 100 CIs. All surgery and post-operative procedures were conducted at Department of Otorhinolaryngology, Head and Neck Surgery, and Audiology, Rigshospitalet, Copenhagen, Denmark.

### Audiological and patient-reported outcome measures

At baseline (T0), all patients were tested with pure-tone audiometry thresholds for six frequencies, ranging from 250 to 8000 Hz (PTA6) and speech reception score (SRS). Two speech recognition tests, Dantale I and Hearing in Noise Test (HINT), and three patient-reported outcome measures (PROMs)—Nijmegen Cochlear Implant Questionnaire (NCIQ), Speech, Spatial, and Qualities of Hearing Scale (SSQ-12), and Tinnitus Handicap Inventory (THI)—were conducted at baseline (T0) and two post-implantation follow-ups (T1 and T2). T0, T1, and T2 coincided with routine clinical follow-up visits. From auditory performance and patient-reported quality of life outcomes (NCIQ and SSQ-12) from an earlier study [25], we will compare these findings to those related to tinnitus.

### Tinnitus outcome measures

The Danish 25-item Tinnitus Handicap Inventory (THI) is a patient-reported outcome measure for tinnitus burden [26, 27]. The patients can answer each item on a scale of "yes" (4 points), "sometimes" (2 points) and "no" (0 points), resulting in a total score of 0–100 points. Patients rated their subjective tinnitus burden on a visual analog scale (VAS) from "No symptoms" to "Worst imagined symptoms" [28]. The VAS score was converted into a scale of 0—100 points. We assessed tinnitus handicap (THI total score) and subjective burden (VAS) before implantation (T0), and at 4 months (T1) and 14 months (T2) after implantation.

The tinnitus severity grading developed by McCombe et al. grades the tinnitus handicap into five severity levels: (1) slight or no handicap (0–16 points), (2) mild handicap (18–36 points), (3) moderate handicap (38–56 points), (4) severe handicap (58–76), and (5) catastrophic handicap (78–100)[29]. The minimal clinically significant change score for tinnitus handicap is seven points, as proposed by to Zeman et al. [30].

### Statistical analysis

All analyses and graphics were conducted in RStudio [31]. Demographic data were examined using means, medians, ranges, and percentages. We analysed and compared pre- and post-operative questionnaire scores to detect significant differences in tinnitus and associated patient characteristics before and after CI. Since THI and VAS are non-normally distributed ordinal scale data, we used non-parametric analysis and reported median and interquartile range (IQR). The Friedman test was used to compare T0, T1 and T2 changes over time. Post hoc Wilcoxon signed-rank test with Bonferroni-adjusted $p$ values was used to do pairwise comparisons. We used Spearman correlation coefficients to examine the strength and direction of correlations between speech reception scores, PROMs, and the change in tinnitus after implantation.

## Results

### Patient characteristics

49 patients were enrolled; however, four were lost to follow-up. Among the 45 included patients, 18 (40%) were female and 27 (60%) were male. All patients were given an ID number that followed them during the study. Patients' age ranged from 26 to 88 years. Pure-tone audiometry in the implanted ears had a mean score (SD) of 89 (16) dB HL, while contralateral ears had a mean score of 79 (17) dB HL. Mean speech reception score (SD) was 24% (22) and 45% (28) for implanted and contralatereal ears. On the implanted ears, 20 patients (44%) had profound hearing loss and 20 patients (44%) had severe hearing loss. On the contralateral ear, 7 patients (16%) had profound hearing loss and 24 patients (53%) had severe hearing loss. The patients had used hearing aids on average for 19 years (range 0–57). Table 1 divides the demographic characteristics into two groups: those who had tinnitus ($n = 31$) during the study and those who did not ($n = 14$). Table 2 shows the individual patient data from the tinnitus group.

The Nucleus Cochlear CI522 ($n = 26$, 58%) or Nucleus Cochlear CI622 ($n = 6$, 13%) electrodes was implanted in most patients. The remaining 21 patients received Oticon Medical Zti EVO ($n = 5$, 11%), Advanced Bionics ULTRA 3D Midscale ($n = 5$, 11%), and MED-EL Flex 28 Synchrony ($n = 2$, 4%). One surgeon implanted 26 CIs (58%), while three other surgeons inserted 10 (22%), 6 (13%), and 3 (7%) CIs. All of the cochlear implant electrode arrays were fully inserted. 39 (87%) patients had normal impedances measured. Impedances were not measured in 6 (13%) of the patients. In 33 (73%), normal eCAP responses were measured. Six patients (13%) had no eCAP response measured. 3 patients had one absent electrode eCAP response, 2 (4%) had two absent electrode contacts, and 1 (2%) had more than three absent electrode contacts.

Non-congenital hereditary SNHL was the etiology of hearing loss in 10 patients (22%), congenital hearing loss in 4 patients (9%) and unknown etiology in 16 (36%) patients. Other causes of hearing loss were found in 15 (33%) patients, including Ménière's disease, otosclerosis, meningitis, and syndromic hearing loss.

**Table 1** Demographic characteristics of patients divided into No tinnitus (n = 14) and Tinnitus (n = 31) groups

| | No tinnitus ($n = 14$) | Tinnitus ($n = 31$) |
|---|---|---|
| Age at implantation (years), median (min, max) | 73 (26, 83) | 66 (27, 88) |
| Gender | | |
| Male | 7 (50%) | 20 (65%) |
| Female | 7 (50%) | 11 (35%) |
| Implanted side | | |
| Right | 6 (43%) | 19 (61%) |
| Left | 8 (57%) | 12 (39%) |
| Duration of hearing aid use before CI (years), median (min, max) | 23 (1, 57) | 16 (0, 53) |
| Pure-tone average (PTA6) | | |
| Implanted ear (dB HL), mean (SD) | 87 (15) | 91 (17) |
| Contralateral ear (dB HL), mean (SD) | 82 (17) | 77 (16) |
| Speech reception score (SRS) | | |
| Implanted ear (%), mean (SD) | 22 (20) | 25 (22) |
| Contralateral ear (%), mean (SD) | 29 (25) | 52 (26) |
| Hearing loss degree in implanted ear | | |
| Moderate (41–55 dB) | 0 (0%) | 0 (0%) |
| Moderately-severe (56–70 dB) | 2 (14%) | 3 (10%) |
| Severe (71–90 dB) | 7 (50%) | 13 (42%) |
| Profound (≥ 91 dB) | 5 (36%) | 15 (48%) |
| Hearing loss degree in contralateral non-implanted ear | | |
| Moderate (41–55 dB) | 1 (7%) | 3 (10%) |
| Moderately-severe (56–70 dB) | 3 (21%) | 7 (23%) |
| Severe (71–90 dB) | 7 (50%) | 17 (55%) |
| Profound (≥ 91 dB) | 3 (21%) | 4 (13%) |

**Table 2** Individual patient outcomes for the tinnitus group ($n=31$)

| Id | Gender | Age at implantation (Y) | Duration of hearing aid (Y) | Impedance | eCAP response | CI ear hearing level (PTA6) (dB HL) | Contralateral ear hearing level (PTA6) (dB HL) | SRS CI ear (%) | SRS contralateral ear (%) | THI total | | | VAS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | T0 | T1 | T2 | T0 | T1 | T2 |
| 1 | Male | 74 | 22 | Normal | Normal | 77 | 52 | 45 | 80 | 60 | 14 | 10 | 93 | 18 | 28 |
| 2 | Male | 71 | 0 | NA | NA | 105 | 106 | 9 | 53 | 38 | 26 | 0 | 72 | 64 | 0 |
| 3 | Female | 51 | 30 | Normal | Absent response in 1 electrode contact | 118 | 78 | 0 | 68 | 38 | 32 | 30 | 80 | 28 | 28 |
| 4 | Female | 43 | 40 | Normal | Normal | 108 | 115 | 0 | 0 | 44 | 40 | 0 | 50 | 54 | 0 |
| 5 | Male | 68 | 14 | NA | NA | 97 | 70 | 0 | 28 | 20 | 12 | 0 | 24 | 15 | 0 |
| 6 | Male | 72 | 9 | Normal | Normal | 98 | 86 | 48 | 33 | 0 | 14 | 0 | 0 | 31 | 0 |
| 9 | Male | 67 | 15 | Normal | Normal | 85 | 88 | 24 | 32 | 28 | 6 | 18 | 38 | 34 | NA |
| 10 | Male | 66 | 30 | Normal | Normal | 109 | 90 | 0 | 45 | 2 | 2 | 0 | 1 | 6 | 18 |
| 11 | Male | 79 | 20 | Normal | Normal | 77 | 68 | 14 | 56 | 25 | 12 | 14 | 64 | 34 | 22 |
| 12 | Male | 67 | 23 | Normal | Normal | 108 | 78 | 0 | 85 | 2 | 10 | 6 | 11 | 17 | 18 |
| 13 | Female | 57 | 53 | Normal | Normal | 92 | 86 | 50 | 68 | 2 | 0 | 0 | 18 | 0 | 0 |
| 14 | Female | 60 | 7 | NA | NA | 76 | 71 | 29 | 28 | 38 | 14 | 16 | 36 | 40 | 36 |
| 15 | Male | 57 | 6 | Normal | Normal | 75 | 78 | 45 | 55 | 60 | 52 | 20 | 94 | 73 | 57 |
| 18 | Male | 86 | 10 | Normal | Normal | 67 | 64 | 56 | 49 | 0 | 0 | 0 | 1 | 0 | 0 |
| 19 | Female | 88 | 20 | Normal | Normal | 78 | 75 | 0 | 0 | 16 | 4 | 6 | 25 | 17 | NA |
| 22 | Male | 72 | 17 | Normal | Normal | 78 | 77 | 39 | 28 | 4 | 2 | 2 | 0 | 10 | 12 |
| 23 | Male | 55 | 18 | Normal | Normal | 98 | 74 | 0 | 77 | 62 | 0 | 0 | 68 | 0 | 0 |
| 24 | Male | 54 | 0 | Normal | Normal | 68 | 72 | 15 | 35 | 24 | 10 | 6 | 60 | 27 | NA |
| 25 | Male | 50 | 0 | Normal | Normal | 102 | 84 | 35 | 85 | 20 | 4 | 12 | 58 | 14 | 3 |
| 28 | Female | 40 | 33 | Normal | Normal | 96 | 85 | 48 | 60 | 10 | 4 | 4 | 15 | 11 | 11 |
| 29 | Female | 38 | 8 | Normal | Normal | 86 | 111 | 40 | 0 | 0 | 56 | 58 | 0 | 63 | NA |
| 30 | Male | 69 | 25 | Normal | Normal | 78 | 74 | 35 | 65 | 6 | 4 | 0 | 2 | 11 | 0 |
| 32 | Female | 27 | 0 | Normal | Normal | 88 | 62 | 31 | 68 | 88 | 48 | 10 | 98 | 59 | 11 |
| 34 | Male | 66 | 20 | Normal | Absent response in > 3 electrode contacts | 56 | 53 | 30 | 40 | 30 | 30 | 20 | 48 | 68 | 65 |
| 35 | Male | 83 | 20 | Normal | Normal | 79 | 59 | 55 | 40 | 18 | 4 | 8 | NA | 6 | 17 |
| 39 | Female | 35 | 7 | Normal | Normal | 112 | 72 | 0 | 75 | 84 | 56 | 46 | 82 | 62 | 26 |
| 40 | Male | 76 | 7 | Normal | Absent response in 2 electrode contacts | 73 | 67 | 41 | 68 | 4 | 26 | 34 | 4 | NA | 30 |
| 42 | Female | 35 | 25 | NA | NA | 73 | 68 | 78 | 72 | 14 | 14 | 10 | 29 | 16 | 20 |
| 43 | Male | 32 | 16 | Normal | Normal | 102 | 91 | 8 | 40 | 6 | 0 | 0 | 5 | 17 | 0 |
| 44 | Male | 77 | 0 | Normal | Normal | 109 | 78 | 0 | 80 | 0 | 0 | 0 | 5 | 0 | 0 |
| 46 | Female | 69 | 2 | Normal | Absent response in 1 electrode contact | 115 | 47 | 0 | 100 | 76 | 46 | 44 | 97 | 98 | 96 |

Two patients (id #18 and #44) reported pre-implantation tinnitus, but neither reported any handicap (THI = 0). Two other patients (id #6 and #29) reported newly developed tinnitus after implantation

*eCAP* electrically Evoked Compound Action Potential, *CI* cochlear implant, *PTA6* pure-tone audiometry average for six frequencies, *dB HL* decibel hearing level, *SRS* speech reception score, *THI* tinnitus handicap inventory, *T0* pre-implantation evaluation, *T1* first post-implantation follow-up, *T2* second post-implantation follow-up, *NA* Not Available

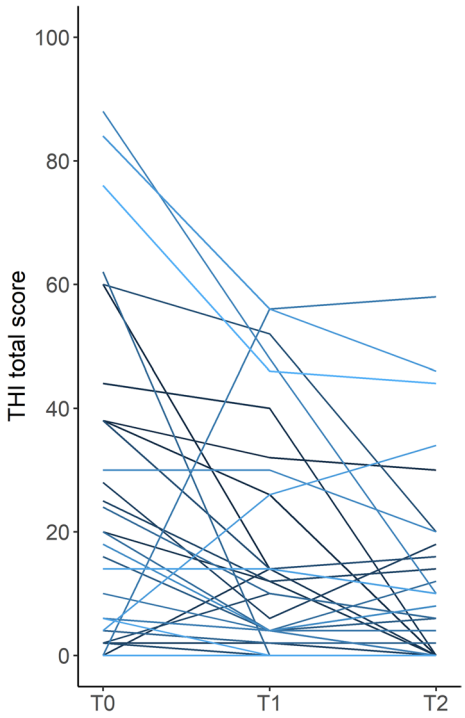


**Fig. 1** Changes in THI total scores for each patient in the tinnitus group ($n = 31$) at the three follow-ups T0, T1 and T2

## Tinnitus outcomes

Postoperative THI responses, T1 and T2, were performed at 4 months (mean 120 days, range 66–220) and 14 months (mean 410 days, range 290–530) after implantation. During the study, tinnitus was experienced by a total of 31 patients (69%). 29 (64%) had tinnitus before implantation, while two patients (4%) developed tinnitus after implantation (Fig. 1). The first patient had no tinnitus at T2, while the other reported persistent severe tinnitus after T2. Tinnitus was totally suppressed in 6 patients (19%) and improved in 15 (48%) patients after CI. Two patients (6%) reported an increase in tinnitus. Tinnitus remained unchanged in 6 (19%) patients (THI change ≤ 7) (Table 3).

The Friedman test showed a statistically significant decrease in THI total scores with time, $\chi^2(2) = 24$, $p < 0.001$. Median (IQR) THI total score was 20 (34) at T0, 12 (24) at T1 and 6 (17) at T2. THI total scores decreased significantly between T0 and T1 ($Z = 284$, $p < 0.05$), between T0 and T2 ($Z = 356$, $p < 0.001$), but not between T1 and T2 ($Z = 226$, $p = 0.091$) (Fig. 2a).

**Table 3** Tinnitus status after second post-implant follow-up (T2)

| | Overall ($n = 31$) |
|---|---|
| Totally suppressed | 6 (19%) |
| Improved | 15 (48%) |
| Worsened | 2 (6%) |
| Unchanged | 6 (19%) |
| No handicap reported | 2 (6%) |

The median VAS score also decreased significantly with time, $\chi^2(2) = 12$, $p < 0.01$. Post hoc test revealed that the median (IQR) VAS scores for T0, T1, and T2 were 33 (62), 17 (40), and 12 (27), respectively. There was a significant decrease in VAS between T0 and T2 ($Z = 269$, $p < 0.01$), and T1 and T2 ($Z = 190$, $p < 0.05$), but not between T0 and T1 ($Z = 300$, $p = 0.228$) (Fig. 2b).

Before the implant, 14 patients (45%) had slight or no handicap, 7 (23%) had mild handicap, 4 (13%) had moderate handicap, 4 (13%) had severe handicap, and 2 (5%) had catastrophic handicap (Table 4). At T2, 23 patients (74%) had slight or no handicap, 5 (16%) had mild handicap, 2 (6%) had moderate handicap, and 1 (3%) had severe handicap. No patients had catastrophic handicap at T2 (Table 4).

## Correlation analyses

The decrease in THI between T0 and T2 was strongly correlated with pre-implant THI scores ($\hat{\rho}_s = 0.95$; $p < 0.001$ (Fig. 3). The decrease in THI between T0 and T2 was likewise strongly correlated with pre-implantation VAS ($\hat{\rho}_s = 0.89$; $p < 0.001$). None of the other factors we analysed showed any correlation to the decrease in THI scores (Table 5).

# Discussion

In the present study, we found that 64% of this cohort of CI recipients with moderate to profound SNHL had tinnitus prior to implantation. Two patients reported newly developed tinnitus; the first had no tinnitus at the second follow-up, while the latter had persistent severe tinnitus. Out of all the patients with tinnitus, complete suppression of tinnitus was observed in 19%, while 48% showed improvement in tinnitus. As a result, 68% of the patients showed an improvement in tinnitus handicap. Two patients (6%) reported worse tinnitus after the second follow-up. Tinnitus in 6 patients (19%) remained unchanged. Tinnitus was reduced in most of the CI recipients within the first 4 months, but we also observed individual reductions after 14 months.

The median THI total score decreased significantly after implantation at both post-implant follow-ups compared to the baseline. Between pre-implant and post-implant follow-ups, the median VAS score was likewise significantly lower, indicating that the recipients were less burdened by their tinnitus following implantation. The decrease in THI scores

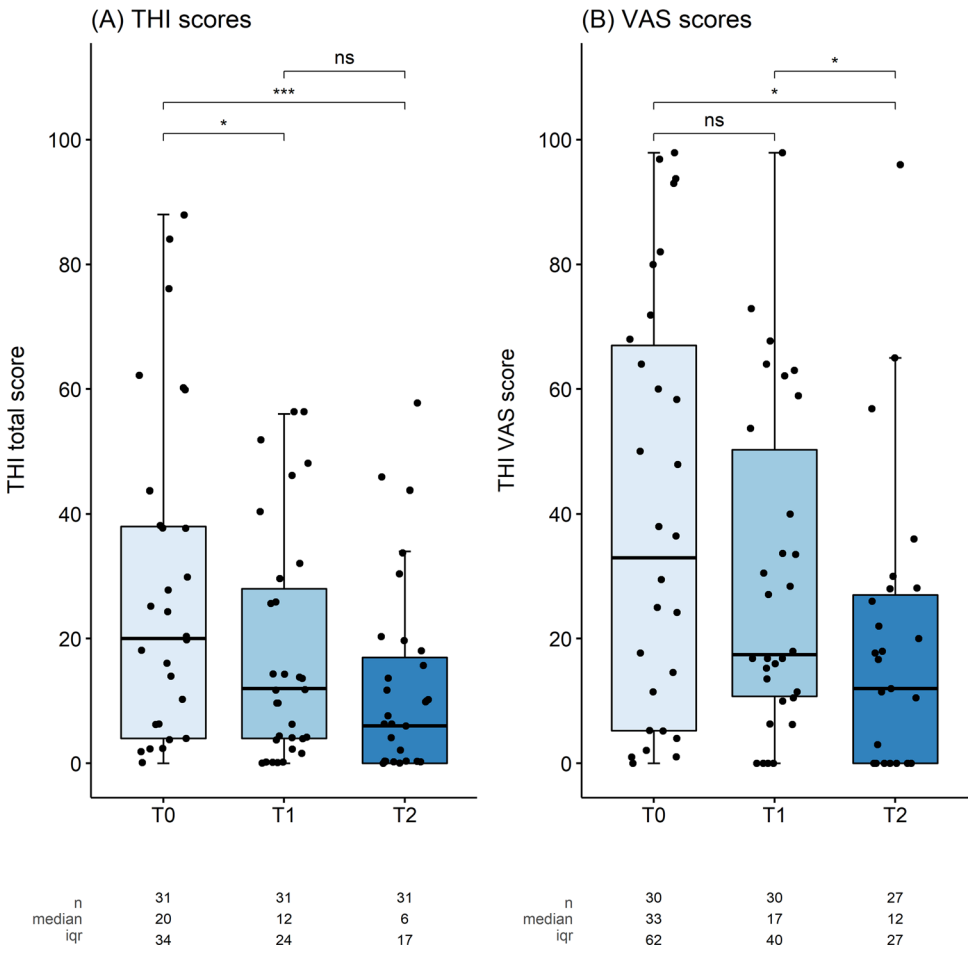


**Fig. 2** Pre- and post-operative **a** tinnitus handicap inventory (THI) scores and **b** VAS scores for patients in the tinnitus group prior to implantation (T0), and at two post-implantation follow-ups (T1 and T2). The boxes represent first and third quartiles (Q1 and Q3), and interquartile range (IQR). The line across the box represents the median. Box plot whiskers stretch from Q1 to minimum and Q3 to maximum. Dots represent individual patients' THI scores. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns: not significant

**Table 4** Tinnitus severity grading in 31 patients with tinnitus

| | T0 ($n=31$) | T1 ($n=31$) | T2 ($n=31$) |
|---|---|---|---|
| Tinnitus severity grading | | | |
| Slight or no handicap (0–16 points) | 14 (45%) | 21 (68%) | 23 (74%) |
| Mild handicap (18–36 points) | 7 (23%) | 4 (13%) | 5 (16%) |
| moderate handicap (38–56 points) | 4 (13%) | 6 (19%) | 2 (6%) |
| severe handicap (58–76 points) | 4 (13%) | 0 (0%) | 1 (3%) |
| catastrophic handicap (78–100 points) | 2 (6%) | 0 (0%) | 0 (0%) |

correlated with pre-implant THI scores and pre-implant VAS, meaning that those patients with higher pre-implant THI and VAS experienced the largest drop in scores after implantation. In summary, we found that following implantation, there was a sustained significant reduction in tinnitus and few incidences of new or worsened tinnitus.

## Comparison to other studies

The pre-implantation tinnitus prevalence (64%) in this cohort is slightly lower than the estimated tinnitus prevalence range of 67–100% found in a review by Baguley et al. [14]. Overall, 68% of patients had their tinnitus handicap reduced, which corresponds to previous studies that ranged between 64 and 100% in unilaterally implanted patients [13, 20, 22, 32, 33]. Previous studies have also reported on tinnitus worsening in a few patients following CI. Amoodi et al. found that tinnitus handicap worsened in 5% of patients [32], while Kompis et al. found that tinnitus worsened in 7–9% of patients after implantation [22]. Kompis et al. also found that 11% (n = 5/47) of patients experienced new tinnitus and found an association between the patients who had tinnitus induced after implantation and poor speech reception [22]. In a study with 35 patients, Kim et al. found no worsening or new tinnitus after CI [20], but in a 2016 study, Kim et al. found newly developed tinnitus in 20% (n = 5/20) of

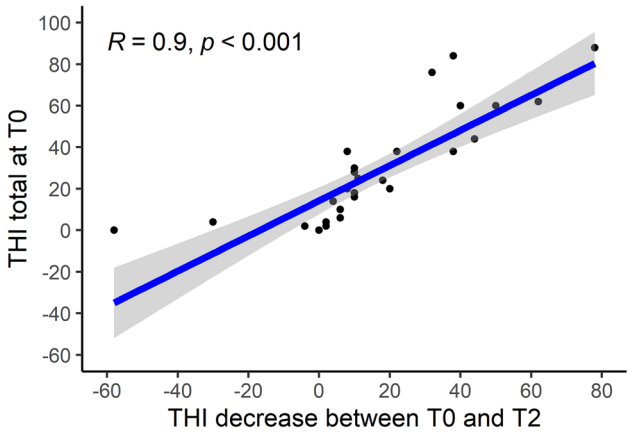


**Fig. 3** The decrease in THI scores between T0 and T2 showed a strong, significant correlation with preoperative THI scores. Spearman's rho ($R$) = 0.95, $p < 0.001$. Blue line represents regression line, gray area is 95% confidence intervals

patients, which resolved later [17]. In our study, two patients (6%) developed tinnitus after implantation, but only one patient (3%) had persistent tinnitus and experienced severe handicap as a result.

The mechanism by which CI can suppress tinnitus is unknown, although a multimodal mechanism including habituation, auditory masking [3], direct cochlear stimulation, and cortical reorganization is postulated. [13]. Punte et al. argue that electrical stimulation of the auditory nerve reverse the plastic reorganization of central auditory cortex associated with peripheral deafferentation that may be the cause of tinnitus [34]. Mallen et al. showed better tinnitus suppression 2 months after CI activation compared to the time of CI activation, indicating that the initial effect of auditory masking can reduce tinnitus in the short term, while neural plasticity suppress tinnitus in the long term [35]. Tinnitus suppression may also be aided by increased awareness of surrounding noises [34]. Bovo et al. reported that CI was able to reduce tinnitus in some patients immediately after implantation, after 6 months and after 18 months of CI use [13]. This finding is consistent with our findings. Although we do not have post-implant outcomes immediately after implantation, we do demonstrate tinnitus reduction after 4 and 14 months of CI use. This study reports longitudinal suppression of tinnitus and continued improvement beyond 14 months of CI use, and this may be due to combination of masking and neural plasticity in the central auditory cortex.

Following CI, 2 of 31 (6%) patients developed new tinnitus, while 2 of 31 (6%) patients with pre-implant tinnitus experienced post-operative tinnitus worsening. These results are comparable to prior findings [14, 19, 22, 36]. The first recipient with newly developed tinnitus

**Table 5** Spearman correlation analyses of the decrease in tinnitus handicap inventory (THI) scores

| | *n* | Correlation coefficient (Spearman $\rho$) | *p* value |
|---|---|---|---|
| Age at implantation | 31 | − 0.20 | 0.286 |
| Duration of HA | 31 | − 0.18 | 0.335 |
| Hearing level (PTA6) in CI ear | 31 | 0.08 | 0.682 |
| Speech reception score (SRS) in CI ear | 31 | − 0.29 | 0.108 |
| Pre-implant THI score | 31 | 0.94 | < 0.001 * |
| Pre-implant VAS | 31 | 0.86 | < 0.001 * |
| Change in Dantale score | | | |
| Best aided in quiet without lip-reading | 31 | 0.11 | 0.874 |
| Best aided in noise without lip-reading | 30 | − 0.03 | 0.124 |
| Change in HINT score | | | |
| HINT sentences in quiet | 16 | 0.00 | 0.996 |
| HINT words in quiet | 16 | − 0.11 | 0.689 |
| HINT sentences in noise | 15 | 0.45 | 0.095 |
| HINT words in noise | 15 | 0.21 | 0.444 |
| Change in NCIQ | 30 | − 0.05 | 0.775 |
| Change in SSQ | 30 | 0.07 | 0.694 |

The decrease in THI between T0 and T2 was strongly correlated with pre-implant THI total scores and VAS scores

*HA* hearing aid, *PTA6* pure-tone audiometry average for six frequencies, *THI* tinnitus handicap inventory, *VAS* visual analog scale for tinnitus burden, *HINT* hearing in noise test, *NCIQ* Nijmegen Cochlear implant questionnaire, *SSQ* speech, spatial and qualities of hearing.

*Significant (Bonferroni-adjusted *p* values)

had tinnitus between T0 and T1, but it resolved by T2. The second recipient did not report any tinnitus at T0 but reported a severe handicap at T1 and T2 (THI total score of 58 and 66). It has previously been shown that patients who experienced tinnitus induced by CI had poor speech reception scores [22]. In our case, the patient did have low PTA6 and SRS at baseline, but this is a topic that needs further research.

### Correlation analyses

Numerous studies have been conducted to assess predictors of speech reception outcomes after CI [37]. In general, research on tinnitus reduction after CI is limited and information on predicting factors for tinnitus burden outcomes is even more limited. Several predictors for tinnitus recovery were reported in two recent investigations, the first by Ramakers et al. [38] and the second by Dixon et al. [39]. Lower speech recognition scores (CVC) at baseline, unilateral tinnitus and loss of residual hearing at 250 Hz were shown to predict tinnitus improvement in the model of Ramakers et al. Dixon et al. likewise demonstrated that poorer residual hearing predict tinnitus recovery, albeit they suggested that, contrary to Ramakers et al., better baseline hearing could result in tinnitus improvement. Furthermore, they found that higher baseline THI scores were associated with a greater likelihood of tinnitus improvement. We also observed that higher THI and VAS scores before implantation was correlated with better tinnitus improvement. We found no effect of age, duration of HA prior to implantation, hearing level or speech reception score in our population. We also found no evidence that improved auditory performance and overall quality of life following implantation will result in less tinnitus.

### Strengths and imitations

The study's strengths include a prospective longitudinal study design assessing benefits before and up to 14 months after implantation. Tinnitus changes are monitored at three time points. According to the findings of this research, tinnitus suppression by cochlear implants is stable, and tinnitus does not reappear over time.

One limitation of the study was that we did not record whether the tinnitus was exclusively in the CI ear, only in the non-CI ear, or bilaterally before surgery. Tinnitus in the contralateral ear may mask a change in tinnitus in the implanted ear that is either decreased or intensified. The patients completed the THI while their CI was switched on. The effects on tinnitus were not examined when the CI was switched off. Quaranta et al. found that 22% of patients had tinnitus when the CI was switched off, but it disappeared when it was switched on. [36]

Tinnitus is often present in specific hearing loss aetiologies, such as Ménière's disease, vestibular schwannomas, and otosclerosis. The etiologic groups in this investigation were too small to provide for meaningful statistical analysis.

### Clinical implications

In addition to the significant audiological improvement observed in the adult CI group [25], there was also a decrease in tinnitus following cochlear implantation. Positive effects on tinnitus have been demonstrated earlier; however, the evidence from the Nordic countries is limited, and to our knowledge, Rodvik et al. from Norway is the only other group to describe tinnitus improvement after CI [40]. Tinnitus should not be considered a disqualifying factor for candidacy, but rather, tinnitus should also be taken into account along with audiological considerations while selecting a patient for CI. Our results are consistent with previous studies and support the use of cochlear implants in borderline cases of hearing loss with concomitant tinnitus [24, 41].

This study adds to the findings from previous studies on tinnitus improvement after CI and documents a positive benefit from CI in addition to the audiological benefits. Patients who receive CI based only on auditory criteria, regardless of tinnitus, may experience tinnitus suppression as a positive side effect of the implantation. Not only is tinnitus reduced, but numerous studies demonstrate a significant improvement in patient quality of life following implantation because of tinnitus reduction, indicating that CI has important clinical benefits in addition to speech perception improvements [8, 9, 32, 33]. Further studies should consider the effect of CI in patients primarily elected for CI due to severe tinnitus. This study may lead to the broadening of recommendations regarding tinnitus as the major reason for CI in conditions such as single-sided deafness. The risk of developing or worsening of tinnitus after implantation is low, but should be discussed in pre-implantation patient counseling [32].

## Conclusions

Our study leads to the following conclusion: tinnitus suppression is a positive side effect of cochlear implantation. Many CI recipients experience pre-implant tinnitus which in most cases are reduced or totally suppressed following implantation. Patients are also less burdened of their tinnitus. The largest tinnitus reduction was observed within 4 months of CI use, but some patients continued improving up to 14 months after implantation. We found a sustained

significant reduction in tinnitus and few incidences of new or worsened tinnitus following implantation. This research adds to the evidence that CI is an effective treatment for severe tinnitus in adults with moderate to profound SNHL, but further studies are needed. Understanding tinnitus suppression will assist defining future clinical recommendations and cochlear implantation criteria.

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**Code availability** All codes for data cleaning and analysis associated with the current submission are available in OSF at https://osf.io/25azh/?view_only=cd198a9c61bc46929b7359572db67523.

**Availability of data and materials** All data generated or analysed during the study are included in this published article and presented in Table 2. The anonymized full datasets are available upon reasonable request from the corresponding author.

## Declarations

**Conflict of interest** The authors declare no conflict of interest.

**Institutional review board statement** The study was approved by The Danish National Committee on Health Research Ethics (H-17034918) and The Danish Data Protection Agency (RH-2017-308).

**Informed consent statement** Informed consent was obtained from all subjects involved in the study.

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