J Chin Med Assoc

ORIGINAL ARTICLE

# Importance of age at 2nd implantation and interimplant interval to the outcome of bilateral prelingually deafened pediatric cochlear implantation

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## Abstract

**Background:** In Taiwan, the number of cases of sequential bilateral pediatric cochlear implantation (CI) is increasing but data regarding its effectiveness and impact of the reimbursement policy are lacking. We examined the speech perception and quality of life (QOL) of bilateral prelingually deaf children who underwent sequential CI, considering the effects of age at the time of second implantation and interimplant interval.

**Methods:** We enrolled 124 Mandarin-speaking participants who underwent initial cochlear implant (CI1) in 2001-2019 and a second CI (CI2) in 2015-2020. Patients were followed up for ≥2 years and were categorized into groups based on age at the time of CI2 implantation (<3.5, 3.6-7, 7.1-10, 10.1-13, and 13.1-18 years) and interimplant interval (0.5-3, 3.1-5, 5.1-7, 7.1-10, and >10 years). We evaluated speech perception, device usage rates, and QOL using subjective questionnaires (Speech, Spatial, and Qualities of Hearing and Comprehension Cochlear Implant Questionnaire).

**Results:** Speech perception scores of CI2 were negatively correlated with ages at the time of CI1 and CI2 implantation and interimplant interval. Older age and a longer interimplant interval were associated with higher nonuse rates for CI2 and worse auditory performance and QOL. Among individuals aged >13 years with interimplant intervals >10 years, up to 44% did not use their second ear. Patients aged 7.1 to 10 years had better speech perception and higher questionnaire scores than those aged 10.1 to 13 and 13.1 to 18 years. Furthermore, patients aged 10.1 to 13 years had a lower rate of continuous CI2 usage compared to those aged 7.1 to 10 years.

**Conclusion:** Timely implantation of CI2 is essential to achieve optimal outcomes, particularly among sequentially implanted patients with long-term deafness in the second ear and no improvement with hearing aids following CI1 implantation. For CI2 implantation, an upper limit of age of 10 years and interimplant interval of 7 years are essential to prevent suboptimal outcomes. These data can provide useful information to implant recipients, their families, and medical and audiological professionals, enabling a comprehensive understanding of the benefits and potential impacts of the timing of CI2 implantation.

**Keywords:** Age at second cochlear implantation; Binaural; Cochlear implant; Inter-implant interval; Quality of hearing; Spatial hearing; Speech perception

## 1. INTRODUCTION

Bilateral cochlear implants (CIs) are increasingly being used worldwide for the management of severe or profound hearing loss in children. Several countries have implemented policies to subsidize or reimburse the costs associated with bilateral CIs.[1,2] In Taiwan, an increasing number of children are undergoing sequential bilateral cochlear implantation due to government reimbursement initiatives. However, there are insufficient data on the effectiveness of this approach and the impact of reimbursement policies.

Previous studies have demonstrated functional benefits in children and young adults who undergo bilateral cochlear implantation, even with a long time interval between the implantations.[3–7] However, Santa Maria et al[8] suggested that sequential implantation should be performed as soon as possible, preferably within 12 months of the initial implant. However, the optimal timing for sequential implantation is unclear, with varying findings regarding the impact of age and interimplant interval. Speech perception outcomes are influenced by individual factors, such as the duration of deafness, age at implantation, interimplant interval, and the etiology of hearing loss. Furthermore, the quality of life (QOL) following implantation significantly

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*Conflicts of interest: The authors declare that they have no conflicts of interest related to the subject matter or materials discussed in this article.*

*Journal of Chinese Medical Association. (2024) 87: 434-441.*

*Received June 28, 2023; accepted November 19, 2023.*

*doi: 10.1097/JCMA.0000000000001068*

affects the psychological and social functioning of patients. Bai and Stephens[9] and Capretta and Moberly[10] revealed that speech-recognition tests have limited predictive value for assessing the QOL of CI recipients.

In a Speech, Spatial, and Qualities of Hearing (SSQ) questionnaire survey, Sparreboom et al[11] found that children who received a second CI exhibited significantly higher scores in spatial hearing, speech perception, and auditory quality 1 year after implantation compared with children with unilateral CIs. Using the Comprehension Cochlear Implant Questionnaire (CCIQ), King et al[12] revealed a significant improvement in the QOL of individuals with bilateral CIs within 1 to 5 years after implantation compared with those with unilateral implants. However, no longitudinal studies on this topic have yet been conducted in Taiwan.

We evaluated speech perception and QOL of children who developed complete deafness in the second ear and did not benefit from the use of hearing aids initially following the first implantation (CI1). These children subsequently underwent second cochlear implantation (CI2). We integrated objective measures of speech perception, subjective questionnaire responses, and usage rate data to determine the optimal age and interimplant interval to which secondary implantation can be delayed while still achieving acceptable outcomes within the general population.

## 2. METHODS

Between February 2015 and January 2020, 172 patients underwent sequential bilateral cochlear implantations at our institution. We excluded patients with intellectual disability, autism, neurological disorders necessitating additional referrals, developmental impairment, congenital anomalies, cochlear nerve agenesis, or serious medical illness. An additional 48 patients were excluded due to age >18 years, preoperative residual hearing and the use of hearing aids in the second ear, progressive hearing loss in the opposite ear with hearing aid use, and limited duration of hearing aid use subsequent to the initial implantation. The study included 124 children and adolescents who received CI1 before the age of 5 years, with Categories of Auditory Performance scores of 0 to 2 and Speech Intelligibility Rating of 1 or 2. These participants were tracked for a minimum of 2 years. Data were collected retrospectively from medical records. Follow-up appointments for CI2 were scheduled at regular intervals, initially every 3, 6, 12, and 24 months, and then once per year. Participants were advised to use CI2 alone for a specified number of hours daily and underwent rehabilitation. Speech perception scores were assessed for two groups: group 1 included 72 patients who were assessed at 1 year and group 2 included 15 patients from group 1 who additionally underwent assessments for sentences and words in diverse quiet and noisy settings at various time intervals. Recipients from group 1 were categorized according to their age at the time of the CI2 (<3.5, 3.6-7, 7.1-10, 10.1-13, and 13.1-18 years)[13–15] and interimplant interval (0.5-3, 3.1-5, 5.1-7, 7.1-10, and >10 years).

### 2.1. Speech perception tests

Regular speech perception assessments were conducted with three tests after cochlear implantation. First, the easy sentence (ES)[16] test consists of 15 sentences with two to 10 words, including one to seven familiar keywords. Second, the difficult or short sentence (SS) test included 20 sentences with two to 12 words, containing one to 10 less-familiar keywords. Third, the phonemically balanced (PB) word recognition test[17] included 25 monosyllabic words.

#### 2.1.1. Hearing test under noise

The participants underwent speech perception tests for Mandarin monosyllables and sentences in the presence of noise. The Mandarin Monosyllabic Word Recognition Test[18] was used to assess monosyllabic word recognition. The hearing performance of CI1 was assessed once, whereas that of CI2 and both CIs was assessed at 3, 6, and 12 months after surgery for CI2.

Participants completed the remaining two questionnaires after at least 12 months of CI2 implantation. For participants aged <10 years, the primary caregivers were asked to complete the questionnaires.

#### 2.1.2. Speech, Spatial, and Qualities of Hearing

SSQ is a 49-item questionnaire that evaluates the auditory experience and abilities of individuals with hearing loss, including speech perception, spatial hearing, and subjective hearing qualities.[19,20] Participants rate their experiences on a scale from 0 to 10, with higher scores indicating better auditory performance. SSQ provides valuable insights into the overall hearing abilities and experiences of individuals with hearing loss.

#### 2.1.3. Comprehension Cochlear Implant Questionnaire

CCIQ is a 28-item questionnaire that assesses the physical, psychological, and social benefits of CI2.[12] Each item is scored from 1 to 5 based on the perceived frequency of experience. Scores >3 indicate improved QOL following CI2 implantation compared with only CI1. The items are categorized into physical, psychological, and social domains. The physical domain has six subdomains, whereas the psychological domain evaluates subjective feelings. The social domain includes two subdomains related to social interactions and functioning. The questionnaire items are presented randomly with some negatively phrased items to reduce response bias.

### 2.2. Statistical analysis

Statistical analysis was performed using SPSS software (version 17.0; SPSS, Inc., Chicago, IL). We used paired samples *t* test and the Mann-Whitney *U* test to compare continuous variables. The Kruskal-Wallis test was used to compare the age at CI2 implantation and interimplant interval among groups. Post hoc Bonferroni correction was applied for multiple comparisons. Spearman's ρ analysis was used to determine the correlation among variables. *p* value <0.05 was considered indicative of statistical significance.

### 2.3. Ethics statement

This study received approval from the Chang Gung Medical Foundation Institutional Review Board (IRB no. 201700469B0). Data were collected retrospectively and anonymized before analysis.

## 3. RESULTS

In total, 72 patients who received CI2 more than 2 years ago were evaluated for speech perception and usage proportion of CI2 (Table 1). The subgroup with age at the time of CI2 implantation of 13.1 to 18 years comprised the highest number of participants (n = 34) but exhibited the lowest test rate (35.3%) and the highest CI2 nonusage rate (44.1%). Furthermore, the subgroup with an interimplant interval >10.1 years had a test rate of only 40.6% and a high CI2 nonusage rate of 43.8%.

Table 2 presents a comparison of demographic characteristics between groups 1 and 2, as well as of speech perception scores among subgroups within group 1 according to the age at CI2 implantation and interimplant interval.

Table 3 presents the clinical and demographic data related to SSQ and CCIQ following CI2 implantation. The age of

**Table 1**

**Speech perception scores of recipients who used CI2 for >1 year according to the age at the time of CI2 implantation and interimplant interval**

| Time characteristics | Number | Test number | Test rate, % | ES | SS | PB | CI2 use, % | CI2 partial use, % | CI2 nonuse, % |
|---|---|---|---|---|---|---|---|---|---|
| CI1 | | 72 | | 91.8, 98 | 86.8, 95 | 89.4, 92 | | | |
| CI1, SD | | | | 17.3 | 20.3 | 13.0 | | | |
| CI2 | 124 | 72 | | | | | | | |
| Age at 2nd implantation, y | | | | | | | | | |
| <3.5 | 17 | 12 | 70.5 | 91.2, 91 | 81.0, 80.0 | 79.8, 86 | 100.0 | 0.0 | 0.0 |
| 3.6-7 | 30 | 22 | 73.3 | 90.3, 96 | 85.1, 92.0 | 87.7, 88 | 96.7 | 0.0 | 3.3 |
| 7.1-10 | 20 | 12 | 60.0 | 84.2, 94 | 77.3, 85.5 | 65.0, 72 | 85.0 | 10.0 | 5.0 |
| 10.1-13 | 23 | 14 | 60.9 | 62.4, 80 | 60.6, 72.0 | 52.3, 68 | 69.6 | 13.0 | 17.4 |
| 13.1-18 | 34 | 12 | 35.3 | 38.5, 27 | 33.3, 27.5 | 40.7, 34 | 35.3 | 20.6 | 44.1 |
| Interimplant interval, y | | | | | | | | | |
| ≤3 | 31 | 20 | 64.5 | 90.0, 93 | 81.3, 87.5 | 80.1, 84 | 100.0 | 0.0 | 0.0 |
| 3.1-5 | 20 | 12 | 60.0 | 91.7, 96 | 88.8, 96.0 | 90.6, 92 | 90.0 | 5.0 | 5.0 |
| 5.1-7 | 13 | 11 | 84.6 | 82.6, 93 | 74.0, 81.0 | 60.8, 68 | 84.6 | 7.7 | 7.7 |
| 7.1-10 | 28 | 16 | 57.1 | 57.6, 72 | 54.0, 68.0 | 47.6, 52 | 71.4 | 10.7 | 17.9 |
| >10.1 | 32 | 13 | 40.6 | 26.9, 24 | 41.7, 40.5 | 35.3, 24 | 34.4 | 21.9 | 43.8 |

CI = cochlear implant; CI1 = 1st implant; CI2 = 2nd implant; ES = mean and median of daily sentence perception test; PB = mean and median of phonetically-balanced word recognition test; SD = standard deviation; SS = mean and median of short sentence perception test.

**Table 2**

**Demographic profile and speech perception scores of participants in groups 1 and 2 according to the age at the time of CI2 implantation and interimplant interval**

| | N | Mean (range) | 2nd CI, ES | 2nd CI, SS | 2nd CI, PB |
|---|---|---|---|---|---|
| Group 1 | 72 | | | | |
| Male | 36 | | | | |
| Female | 36 | | | | |
| Age at 2nd implantation, y | | 8.73 (1.4-18.0) | | | |
| Age at recruitment, y | | 14.05 (4.3-23.6) | | | |
| Duration of 2nd CI use, y | | 5.32 (2.9-20.3) | | | |
| Interimplant interval, y | | 6.26 (0.5-15.8) | | | |
| Group 2 | 15 | | | | |
| Male | 7 | | | | |
| Female | 8 | | | | |
| Age at 1st implantation, y | | 2.8 (0.9-4.3) | | | |
| Age at 2nd implantation, y | | 10.4 (5.8-16.4) | | | |
| Age at recruitment, y | | 15.3 (10.9-21.4) | | | |
| Duration of 2nd CI use, y | | 4.9 (4.2-5.1) | | | |
| Interimplant interval, y | | 7.6 (3.9-12.7) | | | |
| Comparison between age at 2nd implantation within group 1, y[a] | | | | | |
| <3.5 vs 10.1-13.0 | | | 0.159 | 0.913 | 0.008* |
| <3.5 vs 13.1-18.0 | | | 0.000* | 0.002* | 0.000* |
| 3.6-7.0 vs 10.1-13.0 | | | 0.038* | 0.126 | 0.000* |
| 3.6-7.0 vs 13.1-18.0 | | | 0.000* | 0.000* | 0.000* |
| 7.1-10.0 vs 13.1-18.0 | | | 0.000* | 0.002* | 0.001* |
| 10.1-13.0 vs 13.1-18.0 | | | 0.028* | 0.143 | 0.273 |
| Comparison between interimplant interval within group 1, y[a] | | | | | |
| 0.5-3 vs 7.1-10.0 | | | 0.014* | 0.073 | 0.000* |
| 0.5-3 vs >10.1 | | | 0.000* | 0.005* | 0.000* |
| 3.1-5 vs 5.1-7.0 | | | 1.000 | 1.000 | 0.047* |
| 3.1-5 vs 7.1-10.0 | | | 0.026* | 0.026* | 0.000* |
| 3.1-5 vs >10.1 | | | 0.000* | 0.002* | 0.000* |
| 5.1-7.0 vs >10.1 | | | 0.002* | 0.116 | 0.111 |
| 7.1-10.0 vs 3.1-5.0 | | | 0.026* | 0.026* | 0.000* |

Post hoc tests were conducted for multiple comparisons with Bonferroni correction.

CI = cochlear implant; ES = mean and median of daily sentence perception test; N = number; PB = mean and median of phonetically-balanced word recognition test; SS = mean and median of short sentence perception test.

[a]Kruskal-Wallis test.

*$p < 0.05$. Significant differences.

**Table 3**

**The 1-y CCIQ and SSQ scores from patients with bilateral CIs**

| Tests | Number | Mean; median | Range |
|---|---|---|---|
| SSQ | 61 | | |
| Male | 27 | | |
| Female | 34 | | |
| Age at 1st implantation, y | | 2.5; 2.4 | 0.9-6.1 |
| Age at 2nd implantation, y | | 9.4; 9.3 | 1.4-17.8 |
| Age at recruitment, y | | 14.5; 14.6 | 4.2-23.6 |
| Duration of CI1 use, y | | 11.9; 11.9 | 3.4-21.5 |
| Duration of CI2 use, y | | 5.1; 4.9 | 2.9-20.3 |
| Interimplant interval, y | | 6.8; 6.9 | 0.5-15.8 |
| Interval between CI2 and recruitment, y | | 3.3; NA | 2.1-19.5 |
| CCIQ | 46 | | |
| Male | 17 | | |
| Female | 29 | | |
| Age at 1st implantation, y | | 2.5; 2.3 | 0.9-6.1 |
| Age at 2nd implantation, y | | 8.7; 8.8 | 1.4-17.6 |
| Age at recruitment, y | | 13.5; 13.4 | 4.2-23.6 |
| Duration of CI1 use, y | | 11.0; 11.3 | 3.4-21.5 |
| Duration of CI2 use, y | | 4.8; 4.3 | 2.7-20.3 |
| Interimplant interval, y | | 6.2; 6.2 | 0.5-14.2 |
| Interval between CI2 and recruitment, y | | 4.4; NA | 2.0-19.4 |

CCIQ = Comprehensive Cochlear Implant Questionnaire; CI = cochlear implant; CI1 = 1st implant; CI2 = 2nd implant; SSQ = Speech, Spatial, and Qualities of Hearing Scale.

respondents at the time of CI2 implantation was 8.7 to 9.4 years, with a mean usage duration of CI2 of 4.8 years.

Table 4 compares the hearing performance of CI1, CI2, and CI1 + 2 in quiet and noisy conditions for group 2 (n = 15). The CI2 exhibited improved performance within the first 6 months but performed comparatively worse in noisy conditions. CI1 + 2 demonstrated similar scores to CI1, suggesting minimal impact of CI2 in the first year. However, CI1 + 2 had significantly higher scores than CI1 in noisy conditions after 6 months ($p < 0.05$).

Spearman's correlation analysis demonstrated negative correlations between speech perception scores of CI2 and ages at the time of implantation of CI1 and CI2 and the interimplant interval (Table 5). Furthermore, it revealed positive correlations between duration of CI2 use and the three domains of SSQ, as well as negative correlations between the age at the time of CI2 implantation, interimplant interval, and the three domains of CCIQ.

Table 6 compares SSQ scores before and after CI2 implantation. Significant differences were observed in SSQ scores between patients with interimplant intervals ≤10 and >10 years. No significant differences were found among 15 recipients with available preoperative and postoperative SSQ scores or between patients with unilateral and bilateral implants.

Table 7 summarizes average SSQ item scores and CCIQ domain scores after CI2 implantation in various age groups. Patients aged 7.1 to 10 years had higher scores than those aged 10.1 to 13 years, whereas the score significantly decreased among those aged over 13 years. The average scores of all patients were higher than those of patients aged 10.1 to 13 and >13 years.

## 4. DISCUSSION

We examined the largest group of Mandarin-speaking prelingual deaf children in Taiwan who received sequential bilateral CIs. Our results revealed improved speech perception and overall QOL following sequential bilateral CIs. Optimizing the implantation timing and interimplant interval is crucial to maximize these benefits. However, the highest age and maximum interimplant interval that does not lead to unfavorable outcomes in the second ear remain unclear. Although these issues have been addressed in previous studies, further research is needed for Mandarin-speaking prelingually deaf children who receive CIs. We categorized Mandarin-speaking CI recipients into subgroups based on the age at CI2 implantation and interimplant interval. Our findings suggest that individuals with long-term auditory deprivation in the second ear should undergo sequential implantation before the age of 10 years, with an interimplant interval ≤7 years to achieve optimal speech perception scores, usage rates, hearing ability, and QOL.

With regard to the implantation timing, most experts agree that simultaneous bilateral CI is preferable over sequential implantation.[5,12] However, simultaneous bilateral CI is not covered by national insurance in some countries, such as Taiwan. Previous studies have demonstrated that children who undergo sequential bilateral CI can yield significant developmental benefits, even an interimplant interval of 3 to 9 years.[16,21] Korean studies[14] have revealed that the sensitive period for CI2 (12-13 years) with good speech perception scores (80%) is much longer than that of CI1 (7 years), suggesting that CI1 prolongs the sensitive period for CI2. Therefore, although CI2 should be implanted early, it may also be considered at a later age.

Our results emphasize the importance of assessing the adoption rate in addition to speech perception scores and subjective measures (such as auditory performance and QOL). The consistent use of devices is crucial for the benefits of binaural hearing after CI2 implantation. The age group of 7.1 to 13 years was further divided into two subgroups: 7.1 to 10 and 10.1 to 13 years. At the 2-year follow-up, the rate of continuous use of CI2 was lower in the age subgroup of 10.1 to 13 years (70%) than in that of 7.1 to 10 years (85%). The SSQ and CCIQ scores were lower in the age subgroup of 10.1 to 13 years and higher in the age subgroup of 7.1 to 10 years compared with all patients.

These age differences may be mitigated by regular use of CI2 and auditory rehabilitation. Differences in implant compliance

**Table 4**

**Mean CCIQ and SSQ scores for CI1, CI2, and CI1+2 from group 2 participants at different time points**

| Characteristics | Mean, range | ES | SS | PB, | PB, N | LS, Q | LS, + 10 dB | MMRT, Q | MMRT, + 10 dB |
|---|---|---|---|---|---|---|---|---|---|
| Recipients | | | | | | | | | |
| Male, n = 7 | | | | | | | | | |
| Female, n = 8 | | | | | | | | | |
| Age at 1st implantation, y | 2.8 (0.9-4.3) | | | | | | | | |
| Age at 2nd implantation, y | 10.4 (5.8-16.4) | | | | | | | | |
| Age at recruitment, y | 15.3 (10.9-21.4) | | | | | | | | |
| Duration of CI2 use, y | 4.9 (4.2-5.1) | | | | | | | | |
| Interimplant interval, y | 7.6 (3.9-12.7) | | | | | | | | |
| CI1 | | 90.4 (94) | 85.5 (92) | 89.3 (92) | 70.0 (72) | 84.1 (88) | 82.9 (86) | 85.5 (84) | 81.4 (76) |
| CI2, 3 m | | 37.8 (36) | 37.1 (37) | 52.0 (58) | 38.8 (40) | 39.3 (34.5) | 29.5 (25) | 48.3 (55) | 43.5 (44) |
| CI2, 6 m | | 64.5 (70) | 56.3 (58) | 71.0 (74) | 61.8 (60) | 64.2 (64) | 46.9 (45.5) | 74.3 (76) | 69.0 (72) |
| CI2, 12 m | | 71.0 (83) | 71.0 (83) | 77.0 (84) | 64.3 (68) | 65.3 (64) | 55.3 (67) | 77.7 (80) | 66.0 (66) |
| Binaural CI, 3 m | | 88.2 (94) | 89.2 (93) | 87.2 (90) | 79.6 (80) | 80.0 (83) | 80.8 (90) | 84.7 (90) | 84.7 (88) |
| Binaural CI, 6 m | | 92.8 (96) | 88.3 (90.5) | 90.9 (92) | 85.0 (84) | 81.9 (87.5) | 83.0 (90) | 87.0 (90) | 83.8 (88) |
| Binaural CI, 12 m | | 94.3 (96) | 90.2 (91.5) | 91.3 (92) | 82.9 (86) | 86.6 (89) | 84.7 (91) | 85.7 (90) | 85.3 (92) |
| Comparison among CI1, CI2 and binaural CIs at different periods | | | | | | | | | |
| CI1 vs CI2, 3 m | | 0.001* | 0.001* | 0.001* | 0.002* | 0.002* | 0.001* | 0.000* | 0.000* |
| CI1 vs CI2, 6 m | | 0.008* | 0.004* | 0.017* | 0.036* | 0.021* | 0.005* | 0.047* | 0.145 |
| CI1 vs CI2, 12 m | | 0.017* | 0.109 | 0.045* | 0.326 | 0.041* | 0.024* | 0.354 | 0.079 |
| CI1 vs BiI, 3 m | | 0.868 | 0.532 | 0.772 | 0.146 | 0.884 | 0.885 | 0.561 | 0.243 |
| CI1 vs BiI, 6 m | | 0.803 | 0.805 | 0.636 | 0.012* | 0.836 | 0.835 | 0.281 | 0.227 |
| CI1 vs BiI, 12 m | | 0.596 | 0.459 | 0.532 | 0.050* | 1.000 | 0.957 | 0.826 | 0.161 |
| CI2 3m vs CI2 6 m | | 0.008* | 0.011* | 0.073 | 0.022* | 0.003* | 0.016* | 0.004* | 0.005* |
| CI2 6 m vs CI2 12 m | | 0.091 | 0.237 | 0.778 | 0.865 | 0.575 | 0.833 | 0.753 | 0.673 |
| BiI 6 m vs BiI 12 m | | 0.257 | 0.611 | 0.680 | 1.000 | 0.733 | 0.932 | 0.399 | 1.000 |
| CI2 6 m vs BiI 6 m | | 0.002* | 0.001* | 0.009* | 0.001* | 0.016* | 0.002* | 0.006* | 0.001* |
| CI2 12 m vs BiI 12 m | | 0.012* | 0.017* | 0.018* | 0.012* | 0.043* | 0.012* | 0.027* | 0.012* |

+10 dB = a 50-dB auditory signal and 40 dB of noise; 1st = first ear cochlear implant; 2nd = second ear cochlear implant; BiI = binaural hearing after bilateral cochlear implant; CI = cochlear implant; CI1 = 1st implant; CI2 = 2nd implant; ES = daily sentence perception test; LS = long sentence perception test; m = months; MMRT = Mandarin Monosyllabic Word Recognition Test; N = noisy environment; PB = phonetically-balanced word recognition test; Q = quiet environment; SS = short sentence perception test.

*$p < 0.05$. Significant differences.

may also be explained by a later implantation age. Adolescents often exhibit low compliance for parental instructions due to their distinct thoughts, ideas, and attitudes.[1]

We found that patients aged 13.1 to 18 years have poor outcomes, similar to the results of previous studies. Although a few patients who underwent CI2 implantation at the age of 18 years demonstrated remarkable improvement, such cases were rare. Individuals aged 13 to 18 years discontinued CI use before achieving stable mapping; a few individuals terminated CI use within a few months of implantation. We found a significant increase in the nonuse rate of CI2, reaching 44.1% when CI2 was inserted after the age of 13 years and rising further to 43.8% when the interimplant interval exceeded 10 years. When the interimplant interval was 7.1 to 10 years, the nonuse rate increased to 28.6%, including both partial use (10.7%) and nonuse (17.9%). For patients receiving CI2 after the age of 13 years, two-thirds of the patients were not using the implant (Table 1).

Our data reveal negative correlations between speech perception scores (word and sentence) and factors such as age at CI1 implantation, age at CI2 implantation, and the interimplant interval. These findings disagree with several previous studies.[6,7,22] Smulders et al[6] found that a long interval or advanced age at the time of implantations does not necessarily lead to a poor prognosis after CI2 implantation. Friedmann et al[7] revealed significant improvements in adolescents who underwent CI2 implantation at a mean age of 13.5 years and mean interimplant interval of 8.2 years. Furthermore, the age at CI2 implantation and interimplant interval were not predictive of outcomes. Conversely, our results indicate that older age at CI2 implantation and a long interimplant interval lead to unfavorable outcomes. Differences in patient selection, measurement tools, motivation, rehabilitation, and mapping sessions may explain the differences between our findings and these previous studies. In our clinical experience, a short duration of deafness and auditory deprivation, preoperative residual hearing, and long-term consistent use of hearing aids in the second ear following secondary implantation are associated with positive outcomes. In the presence of these factors, age at the time of CI2 implantation and interimplant interval have relatively minor effects on outcomes. We excluded such cases from the present study to accurately evaluate the effects of older age at the time of CI2 implantation and a long interimplant interval on long-term auditory deprivation in the second ear.

A Korean study[15] demonstrated that CI2 ears reached a plateau in word recognition scores after a significantly shorter duration (11-16 months postoperatively) compared with CI1 ears (40-64 months postoperatively; $p < 0.0001$). Among the age subgroups I to IV, the word recognition scores plateaued at 16, 12, 11, and 13 months, respectively, with no significant differences among them. Our results suggest that the maximum benefit of secondary implants is observed within 1.5 years postoperatively.

In the present study, most participants achieved satisfactory outcomes in terms of open-ended speech at 6 months, except for the younger group who exhibited limited attention and most participants aged >13.1 years who could not undergo the test. After the initial 6-month period, the developmental trajectories differed according to the age at the time of CI2 implantation. In group 2 (Table 4), participants underwent CI2

**Table 5**

**Factors influencing the CI2 speech perception score and SSQ and CCIQ subdomain scores at 12 mo**

| Factors | Statistical analysis | 2nd CI sentence (simple) | 2nd CI sentence (difficulty) | 2nd CI PB (words) |
|---|---|---|---|---|
| Age at 1st implantation, y | Correlation coefficient | –0.360** | –0.319** | –0.369** |
| | *p* value | 0.002* | 0.007* | 0.000* |
| Age at 2nd implantation, y | Correlation coefficient | –0.632** | –0.523** | –0.637** |
| | *p* value | 0.000* | 0.000* | 0.000* |
| Interimplant interval, y | Correlation coefficient | –0.589** | –0.476** | –0.597** |
| | *p* value | 0.000* | 0.000* | 0.000* |
| Duration of 1st implantation, y | Correlation coefficient | –0.479** | –0.347** | –0.514** |
| | *p* value | 0.000* | 0.003* | 0.000* |
| **SSQ, N = 61** | | **Speech perception** | **Spatial hearing** | **Quality of hearing** |
| Age at 1st implantation, y | Correlation coefficient | –0.217 | 0.197 | –0.036 |
| | *p* value | 0.098 | 0.135 | 0.789 |
| Age at 2nd implantation, y | Correlation coefficient | –0.124 | 0.155 | –0.085 |
| | *p* value | 0.350 | 0.241 | 0.524 |
| Duration of 2nd CI use, y | Correlation coefficient | 0.274* | 0.310* | 0.300* |
| | *p* value | 0.036 | 0.017 | 0.022 |
| Interimplant interval, y | Correlation coefficient | –0.089 | 0.120 | –0.080 |
| | *p* value | 0.501 | 0.365 | 0.548 |
| **CCIQ, N = 46** | | **Physical score** | **Psychological score** | **Social score** |
| Age at 1st implantation, y | Correlation coefficient | –0.008 | –0.034 | –0.179 |
| | *p* value | 0.946 | 0.777 | 0.135 |
| Age at 2nd implantation, y | Correlation coefficient | –0.587** | –0.324* | –0.504** |
| | *p* value | 0.000** | 0.032* | 0.000** |
| Duration of 2nd CI use, y | Correlation coefficient | 0.191 | 0.184 | 0.160 |
| | *p* value | 0.214 | 0.232 | 0.300 |
| Interimplant interval, y | Correlation coefficient | –0.522** | –0.311* | –0.423** |
| | *p* value | 0.000** | 0.040* | 0.004** |

Correlation coefficient is analyzed via Spearman's ρ analysis.

CCIQ = Comprehensive Cochlear Implant Questionnaire; N = numbers; SSQ = Speech, Spatial, and Qualities of Hearing Scale.

*$p < 0.05$ indicates statistical significance (two tailed).

**$p < 0.01$.

**Table 6**

**Comparison of SSQ subdomain scores between unilateral and bilateral CIs among the 15 patients who completed SSQ before and after CI2 implantation**

| Same subject | No | Interimplant interval | Age at 2nd implantation | Duration after implant | Speech perception | Spatial hearing | Quality of hearing |
|---|---|---|---|---|---|---|---|
| CI1 | 15 | | 03.4 | 13.3 | 76.5 ± 24.1 | 72.6 ± 40.0 | 115.5 ± 38.2 |
| CI2 | 15 | 8.5 ± 3.1 | 12.0 | 01.6 | 82.1 ± 35.8 | 73.3 ± 43.6 | 115.5 ± 34.7 |
| *p* | | | | | 0.480 | 0.884 | 0.884 |
| | | ≤10 | | | 5.48 ± 1.91 | 4.61 ± 3.14 | 5.86 ± 2.86 |
| | | > 10 | | | 4.95 ± 2.83 | 4.15 ± 2.19 | 5.85 ± 2.04 |
| *p* | | | | | 0.013* | 0.022* | 0.024* |
| One-sided CI | 38 | | 4.8 | 13.2 | 75.0 ± 30.2 | 72.5 ± 41.5 | 106.0 ± 40.3 |
| Two-sided CIs | 66 | | 12.4 | 4.9 | 81.4 ± 27.8 | 79.2 ± 36.1 | 139.8 ± 194.5 |
| *p* | | | | | 0.353 | 0.360 | 0.537 |

CI = cochlear implant; CI1 = 1st implant; CI2 = 2nd implant; interimplant interval = age of 2nd implantation and duration after implant were calculated in years; SSQ = Speech, Spatial, and Qualities of Hearing Scale.

*$p < 0.05$ indicates statistical significance.

implantation after the age of 10.4 years and an interimplant interval >7.6 years; they showed no significant improvements in speech perception scores (sentence and word) during 6 to 12 months postoperatively. During 6 to 12 months postoperatively, sentence test scores slightly increased for the second ear. These findings are in line with those of previous studies.[23,24] Conversely, patients who underwent CI2 implantation at <7 years, or at the latest by 10 years, exhibited good auditory performance during 6 to 12 months postoperatively, with similar sentence and word scores between CI2 and CI1 (Table 1). In group 2, CI1 consistently outperformed CI2 in all tests at all time points up to 12 months. However, in noisy conditions, the test performance was significantly different between CI1 + 2 and CI1 after 6 months ($p < 0.05$).

**Table 7**

**SSQ and CCIQ scores among patients with binaural CIs**

| | SSQ, mean (median) scores | | | CCIQ, mean (median) scores | | |
|---|---|---|---|---|---|---|
| Age at 2nd implantation, y | Speech perception | Spatial hearing | Quality of hearing | Physical score | Psychological score | Social score |
| <3.5 | 6.4 (6.3) | 6.6 (5.9) | 7.9 (7.7) | 3.7 (3.6) | 4.0 (4.0) | 3.8 (3.9) |
| 3.6-7.0 | 6.7 (6.9) | 5.7 (5.9) | 7.7 (7.8) | 3.7 (3.8) | 4.1 (4.1) | 3.9 (4.0) |
| 7.1-10.0 | 7.0 (7.0) | 6.8 (6.8) | 7.7 (7.8) | 3.4 (3.5) | 4.0 (4.0) | 3.5 (3.4) |
| 10.1-13.0 | 6.1 (6.1) | 4.0 (3.5) | 6.6 (6.7) | 2.5 (3.0) | 2.7 (3.3) | 2.4 (3.2) |
| 13.1-18.0 | 5.4 (5.3) | 5.4 (4.8) | 6.4 (6.2) | 2.6 (2.9) | 3.6 (3.5) | 2.9 (3.0) |
| No grouped | 6.3 (6.1) | 5.5 (5.7) | 7.1 (7.3) | 3.2 (3.4) | 3.7 (3.8) | 3.3 (3.4) |

CI = cochlear implant; CCIQ = Comprehensive Cochlear Implant Questionnaire; SSQ = Speech, Spatial, and Qualities of Hearing Scale.

Ramakers et al[25] demonstrated that objective tests alone cannot comprehensively evaluate the subjective aspects of real-life listening situations following CI. Therefore, CI patients should undergo regular objective and subjective tests. CCIQ evaluates the psychological, physical, and social domains, revealing overall improvement 2 years after CI2 implantation. The psychological domain demonstrated the highest scores, whereas speech perception in noisy environments demonstrated the lowest scores. Our patients experienced increased self-confidence, improved social interaction, and enhanced listening ability in quiet environments and music perception, with no adverse effects on vestibular function.

Despite the small number of participants in each age group (8 to 15 individuals), the 2-year assessment demonstrated higher mean and median CCIQ and SSQ scores for the subgroup of age 7.1 to 10 years than those of ages 10.1 to 13 and 13.1 to 18 years.

Ramakers et al[25] found a moderate correlation ($r$ = 0.59) between the spatial hearing domain of SSQ and objective localization testing. In our study, we assessed the subjective spatial hearing domain and observed significantly enhanced direction recognition abilities following second CI2 implantation. The mean score of the SSQ spatial hearing domain was significantly higher in the subgroup of age 7.1 to 10 years (6.8) than that of age 10.1 to 13 years (4.0). In conclusion, our analysis emphasizes the importance of early CI2 implantation, preferably before the age of 10 years, with a maximum interimplant interval of 7 years. These findings offer useful information for implant recipients, families, medical and audiological professionals, and government agencies involved in decision-making and funding for CI2 implantation. Improved postoperative support, rehabilitation measures, and preoperative data sharing can further enhance the outcomes. This study had several limitations. First, given that the study collected data from a single hospital, our results have limited generalizability. Second, challenges posed by schooling during the COVID-19 pandemic hindered participation in this study. Third, the study had a limited statistical power due to the small number of patients in various age and interimplant interval subgroups. To effectively address these limitations, further studies with more participants in each group and longitudinal follow-up are needed. Furthermore, future studies should collect data from multiple institutions and diverse languages.

In conclusion, timely CI2 implantation is crucial for optimal outcomes. For sequentially implanted patients who have experienced long-term deafness in the second ear, we recommend CI2 implantation before the age of 10 years and a maximum interimplant interval of 7 years to achieve optimal outcomes. Avoiding CI2 implantation after the age of 13 years or interimplant interval exceeding 10 years is advisable. These findings can guide implant recipients, their families, and medical professionals about the optimal implantation timing and its potential impacts.

## ACKNOWLEDGMENTS

This study was supported by the Chang-Gung Memorial Hospital Research Program (CMRPG3G1061-3).

The authors thank all of the members of the Department of Otorhinolaryngology-Head and Neck Surgery, New Taipei Municipal TuCheng Hospital (Built and Operated by Chang Gung Medical Foundation), Chang Gung Memorial Hospital, Linkou, for their invaluable help. The authors would like to thank all the recipients and their families who participated in the study.

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