ORIGINAL ARTICLE

Communication Benefits of Bilateral Cochlear Implantation. Retrospective Study in 12-Year-Old Children☆

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Abstract

Introduction and objectives: Some studies suggest that simultaneous or sequential cochlear implantation in a short period of time offers additional benefits. There is a controversy regarding the existence of an age limit after which a second implantation offers less benefit for the acquisition of communication skills. The objectives of this study were to confirm that sequential cochlear implantation offers benefits compared to unilateral implantation and to study whether, at 12 years of age, there are significant differences regarding the age at the time of the second implantation.

Methods: Descriptive and observational study of a population of 12-year-old children carrying cochlear implants (n=69). A liminal pure tone audiometry and an open-field verbal discrimination test (disyllables, common phrases in an open context, with and without noise) were conducted to evaluate audiological benefits.

Results: Verbal discrimination results were better among patients who had been implanted before the age of 2 years, although the differences were not statistically significant (P>.5). Children who had received bilateral cochlear implants before the age of 2 years and with a period less than 4 years between both implants presented better verbal discrimination percentages (P<.05).

Conclusions: In our sample, early cochlear implantation with a short period between both implants provided significant benefits regarding intelligibility. There seem to be a specific age and interimplant period, after which the auditory benefit on the first implant becomes reduced.

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KEYWORDS
Sequential cochlear implantation; Children; Language development

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Introduction

Hearing plays a fundamental role in the acquisition, development and maintenance of speech and language abilities. Children throughout the world acquire the basic vocabulary and essential grammar of their mother tongue during first 4 years of their life. Later, they will add other, more complex, grammatical structures, while their vocabulary will increase throughout their lives.

Any problems with the acquisition of this ability will affect the overall development and learning of a child.

Before the development of hearing aids, most children with moderate to severe bilateral hearing loss (or hypoacusis) failed to develop spoken language. As a result, these children suffered significant limitations to communicate and sign language became the best option to achieve some form of social interaction. Later, to achieve this objective, it was necessary that the prostheses were adapted at an early age, so as to make the most of the plasticity of the pathways and developing auditory cortex. It soon became evident that there was an age after which prosthetic adaptation was relatively ineffective.

Until the introduction of cochlear implants (CI) in the 80s, these benefits could not be achieved in cases of profound hearing loss. The development of this technology allowed many patients with profound hearing loss to obtain benefits similar to those achieved with hearing aids in children with moderate to severe hearing loss. Today, it is widely accepted that, in the absence of other deficiencies, children with profound hearing loss who undergo CI implantation at an early age have the opportunity to acquire a perception of language which is sufficient to develop spoken language and can even follow ordinary schooling.

Some studies suggest that simultaneous or sequential CI within a short period of time provides certain additional benefits, particularly regarding directional hearing.

The present study was designed to investigate the possible existence of an age limit after which a second CI is less effective, clearly offering less benefit or no benefit for the acquisition of communication skills compared to a unilateral CI.

The objectives of this study are to evaluate the auditory outcomes obtained in children who underwent cochlear implantation between the ages of 0 and 5 years, in order to study whether, at 12 years of age, there is a significant difference in hearing outcomes related to age at implantation, and whether sequential bilateral implantation provides an additional benefit over unilateral implantation.

Material and Methods

Environment and Subjects

This was a transversal, observational, descriptive study on a population of 69 subjects aged 12 years, all of whom underwent implantation before the age of 5 years.

A total of 57 children, 31 of them with unilateral CI and 26 with bilateral CI, met the selection criteria established: 12 years of age, CI between the ages of 0 and 5 years, unilateral or successive bilateral cochlear implants with a period less than or equal to 7 years between the first and second CI, experience of over 36 months in the use of processors, and complete insertion of the electrode array in the cochlea.

We excluded those patients who could not participate in the assessments due to disability or disease associated...
to hearing loss, as well as those patients with retrocochlear disease or those in whom full insertion of the electrode array into the cochlea was not achieved. Neither did we include in the study those patients who underwent simultaneous bilateral implantation or sequential with a period exceeding 7 years between the first and second CI.

The study was approved by the corresponding Ethics Committee. Furthermore, in all cases we requested that both parents and legal guardians signed an informed consent form for participation in the study.

**Instrumentation**

From the medical history we noted the aetiology of deafness, the type of hearing loss and the use of hearing aids prior to implantation, in order to characterise the auditory history of patients.

Regarding the CI, we recorded the age at implantation, the processor device and model. For patients with successive, bilateral implants we took into account the time elapsed between the first and second implantations.

Auditory performance was assessed with an Audiotest 240 Interacoustic A/S DK-5610 Assens Denmark 2088CE0123 audiometer, an Ambit 106 LoudSpeaker EU, Ecler SA speaker set, and a cabin with a sound field calibrated at 65 dB without lip reading, with patients seated at a distance of 1 m and an azimuth angle of 0° from the speaker emitting the speech signals. We performed a free field tone audiometry at 65 dB and speech tests in silence and with noise (SNR=10), using a list of disyllable words and everyday phrases adapted to children from the protocol for the assessment of hearing in the Spanish language. In patients with bilateral implantation, audiological assessment was performed binaurally and separately for each CI.

**Statistical Analysis**

Data were stored and processed using OpenOffice tools and processed statistically using the software package SPSS® Statistics v.20.0.

We performed a descriptive analysis of the results obtained through the postoperative observations. Given the sample size of the study, we used parametric hypothesis comparison testing: means were compared using the Student t test for paired data, considering as statistically significant a value of P<.5.

**Results**

**Descriptive Analysis**

The sample consisted of 57 children aged 12 years; 32 girls (56.14%) and 25 boys (43.86%). The aetiology of hearing loss was unknown in 31 cases (54.38%) and familial in 12 cases (21.05%). In 22.8% of cases it was attributable to exposure to ototoxic agents (6 patients), syndromes associated with deafness (4 patients), CMV viral infection (2 patients) and bacterial meningitis (2 patients).

The onset of hearing loss was prelingual in all patients.

Prosthetic adaptation prior to CI was possible in 8 children (11.6%), 6 unilateral and 2 successive bilateral. The period of hearing aid use before implantation in unilateral patients was between 3 and 6 months, whereas usage time in successive bilateral patients reached 18 months.

Implantation category was unilateral in 31 patients (54.38%) and successive bilateral in 26 patients (45.62%).

The mean age at the time of the first implant was 2.77 years (range: 1–5 years). In patients with sequential bilateral implantation, the second implant was placed at a mean age of 6.65 years (range: 4–9 years), with the mean period elapsed between the first and second implant being 4.23 years (range: 2–7 years).

Regarding the CI model used, in unilateral patients it was Nucleus® 24K in 35.5% of cases (n=11), Nucleus® 24 Contour in 22.6% (n=7) and Nucleus® 24 Contour Advance and Freedom™ Implant Contour Advance in 42% (n=13). In patients with sequential implants, regarding the first CI the model used was Nucleus® 24K and Nucleus® 24 Contour in 80.8% of cases (n=21) and Freedom™ Implant Contour Advance in 19.2% (n=5). Regarding the second CI, in 96.2% of cases (n=25) it was Nucleus® Freedom™ Implant Contour Advance and in 3.8% (n=1) it was Nucleus® CI512 model.

Among patients with unilateral CI, the processor used was the Freedom™ in 27 cases (87.1%). In the remaining cases (n=4; 6.45%), the processors used were SPrint™ or CP810.

Out of the children using bilateral processors, 84.62% (n=22) used the Freedom™ processor model, 11.54% (n=3) used a Freedom™ processor in 1 ear and an ESpirt™ 3G in the contralateral, and only 1 bilateral patient (3.85%) had 2 CP810 type speech processors.

All the children (100%) followed speech rehabilitation from the time of activation until the time of the study.

In total, 45 children (78.95%) attended regular schools, whereas 12 patients (21.1%) attended specialised centres.

**Audiological Assessment. Patients With Unilateral Cochlear Implants**

In patients with a right unilateral CI we observed a mean, free field auditory threshold of 28.94±7 dB. The mean discrimination rate of disyllable words was 89.17±10% in quiet environments, and 81.56±13% in noisy environments. The discrimination rate for sentences was 80.10±12%, and 72.77±14% in noisy environments.

In patients with a left unilateral CI we observed a mean, free field auditory threshold of 27.8±5.3 dB. The mean discrimination rate of disyllable words was 84.8±14%, and 74.8±15% in noisy environments. The mean discrimination rate for sentences was 79.7±12%, and 68±14% in noisy environments.

Tables 1 and 2 display the free field average hearing threshold (AHT) by age group, as well as the discrimination rate of disyllables and phrases, with and without ambient noise in patients with right and left unilateral CI, respectively. The AHT and speech discrimination tests showed better results in the group of patients implanted before 2 years. Figs. 1 and 2 graphically represent the discrimination rates for disyllables and sentences in free field, respectively, for patients with unilateral CI by age group: the results in
all the tests were better for patients who underwent early implantations.

### Audiological Assessment. Patients With Bilateral Cochlear Implants

In patients with bilateral sequential CI we observed a free field AHT of 29.04±6.4 dB. The mean discrimination rate of disyllable words was 92.88%±6.5%, and 82.69%±9.4% in noisy environments. The mean discrimination rate for sentences was 78.42%±10% in quiet environments, whereas for noisy environments it dropped to 69.4%±12%.

Table 3 displays the free field average hearing threshold (AHT) by age group at the time of implantation, as well as the discrimination rate of disyllables and phrases, with and without ambient noise in patients with bilateral CI. Fig. 3 presents the discrimination rates for disyllables and sentences in free field for patients with bilateral CI by age group at the time of the CI. The AHT and speech discrimination tests showed better results in the group of patients implanted before they reached 2 years.

### Bivariate Analysis

Within the sample, we found no statistically significant differences in speech discrimination tests by age groups at the time of implantation, both in unilateral CI and bilateral CI patients (\(P>.05\)).

Patients with bilateral CI implanted in the first 2 years of life and with a period under 4 years between the first and second implants displayed better discrimination rates for disyllables and sentences in quiet environments, as well as for disyllables (\(P=.045\)) and sentences in noisy environments (\(P=.006\)).

### Discussion

Neural plasticity is critical in the development of the auditory system. It is widely accepted that there is an age limit after which auditory rehabilitation does not allow the acquisition of spoken language due to cerebral cortex reorganisation phenomena.\(^{1/2}\) The establishment of neonatal screening programs with early referral to specialised

### Table 1

Patients With Right Unilateral CI: Free Field AHT and Discrimination Rates for Disyllables With and Without Noise.

<table>
<thead>
<tr>
<th>Group</th>
<th>AHT (dB)</th>
<th>Disyllables WON (%)</th>
<th>Disyllables WN (%)</th>
<th>Sentences WON (%)</th>
<th>Sentences WN (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–2 years Mean</td>
<td>28.4</td>
<td>88.7</td>
<td>81.9</td>
<td>81.4</td>
<td>75.5</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>6.6</td>
<td>12.5</td>
<td>14.7</td>
<td>13.8</td>
</tr>
<tr>
<td>3–5 years Mean</td>
<td>29.7</td>
<td>89.6</td>
<td>81.2</td>
<td>78.8</td>
<td>70.2</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>7.7</td>
<td>9.5</td>
<td>12.9</td>
<td>11.4</td>
</tr>
<tr>
<td>Total Mean</td>
<td>28.9</td>
<td>89.1</td>
<td>81.5</td>
<td>80.1</td>
<td>72.7</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>7.1</td>
<td>10.9</td>
<td>13.6</td>
<td>12.6</td>
</tr>
</tbody>
</table>

AHT: average hearing threshold; WN: with ambient noise; WON: without ambient noise.

### Table 2

Patients With Left Unilateral CI: Free Field AHT and Discrimination Rates for Disyllables With and Without Noise.

<table>
<thead>
<tr>
<th>Group</th>
<th>AHT (dB)</th>
<th>Disyllables WON (%)</th>
<th>Disyllables WN (%)</th>
<th>Sentences WON (%)</th>
<th>Sentences WN (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–2 years Mean</td>
<td>27.1</td>
<td>86.1</td>
<td>74.4</td>
<td>81.9</td>
<td>72.5</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>4.9</td>
<td>16.9</td>
<td>16.9</td>
<td>13.7</td>
</tr>
<tr>
<td>3–5 years Mean</td>
<td>28.5</td>
<td>83.6</td>
<td>75.2</td>
<td>77.7</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>5.7</td>
<td>11.8</td>
<td>13.9</td>
<td>10.7</td>
</tr>
<tr>
<td>Total Mean</td>
<td>27.8</td>
<td>84.8</td>
<td>74.8</td>
<td>79.7</td>
<td>68.1</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
<td>5.3</td>
<td>14.3</td>
<td>15.2</td>
<td>12.3</td>
</tr>
</tbody>
</table>

AHT: average hearing threshold; WN: with ambient noise; WON: without ambient noise.
auditory centres has increased the early diagnosis of congenital hearing loss and early auditory rehabilitation.

Under normal conditions, the peripheral and central auditory systems receive auditory stimuli presented by both ears. Listening with 2 ears produces a better and more accurate performance of speech perception than monaural listening. As early as 1991, Pijl suggested that a CI in 1 ear had a positive impact on performance in speech perception, but that implantation in both ears could have an even greater positive impact.9,10

Dunn et al. presented results for speech perception in quiet and in noisy environments which were significantly better after the subjects underwent a second CI. In a different study, the same authors showed a significant benefit of bilateral CI in a word test in a silent environment, thus supporting the hypothesis that bilateral CI could be more beneficial than unilateral CI.11,12 In turn, Ramos Macias et al studied 90 implanted children and showed that bilateral CI, performed simultaneously and sequentially with a short period between implants, enabled the acquisition of binaurality.13

The benefit obtained by patients with congenital profound hearing loss is the result of an early activation of the ascending auditory pathways. From the superior pathways to the cochlear nuclear ipsilateral to the CI, they develop bilaterally up to both auditory cortexes, so that a single CI will activate the majority of the ascending pathways on both sides up to the developing brain.8,14 However, neurons in the spiral ganglion and cochlear nucleus corresponding to the non-implanted ear will not receive direct stimulation from

<table>
<thead>
<tr>
<th>Table 3 Patients With Bilateral CI: Free Field AHT and Discrimination Rates for Disyllables With and Without Noise.</th>
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</thead>
<tbody>
<tr>
<td><strong>AHT (dB)</strong></td>
</tr>
<tr>
<td>Group</td>
</tr>
<tr>
<td>1–2 years</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Standard deviation</td>
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<tr>
<td>3–5 years</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Standard deviation</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Standard deviation</td>
</tr>
</tbody>
</table>

AHT: average hearing threshold; WN: with ambient noise; WON: without ambient noise.

**Figure 1** Disyllable word test: unilateral patients.

**Figure 2** Sentence test: unilateral patients.
the implanted cochlea, and this will have a negative effect on their maturation and survival. Without stimulation, the neural elements of this cochlear nucleus will fail to develop and will tend towards degeneration and apoptosis. The existence of a critical age for the second CI and the expectations that this implant provides an adequate level of speech perception are, therefore, consistent and relevant.

In children with congenital profound hearing loss who are successfully implanted unilaterally, there is some controversy regarding whether, upon receiving a second CI after a certain period of time, the first implant will become useless or else there is a limited period after which the second implant will not provide additional benefit in terms of speech discrimination. Peters et al. showed that children who received a second implant between the ages of 8 and 13 years achieved verbal discrimination rates of 40% using only the second implant and 85% using only the first implant. According to another study, children who received a second CI at earlier ages (from 5 to 8 years) showed mean results of 60% in the Lexical Neighbourhood Test (Kirk et al.) with only the second implant, compared to 75% with only the first implant. Mok et al. considered that children with bilateral implants with a long period between both implants seemed to maintain a dominant ear (the more experienced), which somehow prevented them from achieving the benefits of binaurality in some hearing conditions. In turn, Graham proposed an age limit of 18 months for an optimal use of the second implant.

After analysing the verbal discrimination results within our sample, we noted that, among patients with sequential implants, those who were implanted before the age of 2 years and with a period less than or equal to 4 years between both implants presented significantly better results in speech discrimination tests, with and without noise, than those implanted after the age of 2 years and with a period longer than 4 years between both implants.

This finding suggests that a short period between the first and second implants improves speech discrimination, possibly because bilateral auditory stimulation facilitates the acquisition of binaural hearing.

Conclusions

Our data suggest that, in children with prelingual hearing loss, early intervention through unilateral or sequential CI, where implantation is carried out before the age of 2 years, offers better results regarding the development of speech and linguistic competency at the age of 12 years compared with children implanted after the age of 3 years.

In sequential implantation, those children implanted under the age of 2 years of age and with a short period between both implants acquire the benefits of binaurality.

Conflict of Interest

The authors declare no conflict of interest.

References