ORIGINAL ARTICLE

Bilateral Cochlear Implants in Children: Acquisition of Binaural Hearing

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KEYWORDS
Cochlear implants; Bilateral; Binaural; Simultaneous; Sequential

Abstract

Introduction and objectives: Several studies have indicated the benefit of bilateral cochlear implants in the acquisition of binaural hearing and bilateralism. In children with cochlear implants, is it possible to achieve binaurality after a second implant? When is the ideal time to implant them? The objective of this study was to analyse the binaural effect in children with bilateral implants and the differences between subjects with simultaneous and sequential implants with both short and long intervals.

Patients and methods: There were 90 patients between 1 and 2 years of age (the first surgery), implanted between 2000 and 2008. Of these, 25 were unilateral users and 65 bilateral; 17 patients had received simultaneous implants, 29 had sequential implants before 12 months after the first one (short interimplant period) and 19 after 12 months (long period). All of them were tested for silent and noisy verbal perception and a tonal threshold audiometry was performed.

Results: The silent perception test showed that the simultaneous and short period sequential implant patients (mean: 84.67%) versus unilateral and long period sequential implants (mean: 76.66%), had a statistically significant difference (P=.023). Likewise, the noisy perception test showed a difference with statistical significance (P=.002) comparing the simultaneous implanted and short period sequential implants (mean: 77.17%) versus unilateral implanted and long period sequential ones (mean: 69.32%).

Conclusions: The simultaneous and sequential short period implants acquired the advantages of binaural hearing.

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**PALABRAS CLAVE**
Implantes cocleares; Bilateral; Binaural; Simultáneo; Secuencial

**Implantes cocleares bilaterales en la población infantil: adquisición de la binauralidad**

**Resumen**

*Introducción y objetivos*: Numerosos estudios han señalado el beneficio de los implantes cocleares bilaterales en la adquisición de la binauralidad y la bilateralidad. En los niños portadores de un implante coclear, ¿se conseguiría adquirir la binauralidad tras un segundo implante? ¿Cuándo sería el momento ideal para implantarlos? El objetivo del estudio es analizar el efecto binaural en niños con implantes bilaterales y analizar las diferencias entre los sujetos implantados de manera simultánea y de manera secuencial con un intervalo corto y otro largo.

**Pacientes y métodos**: Se incluyeron 90 pacientes implantados con una edad comprendida entre uno y 2 años (primera cirugía), entre 2000 y 2008. Veinticinco niños eran usuarios unilaterales y 65 bilaterales, 17 implantados simultáneamente, 29 implantados de forma secuencial, realizándose el segundo implante antes del año (corto periodo interimplante) y 19 secuenciales en los que el segundo implante se realizó posteriormente al año de la primera cirugía (largo periodo interimplante). A todos los pacientes se les realizó la prueba de percepción verbal en silencio, en ruido y una audiometría tonal lineal.

**Resultados**: Prueba de percepción verbal en silencio: implantes simultáneos y secuenciales con corto periodo entre implante (media: 84,67%) frente a los implantes secuenciales con largo periodo entre implantes y los unilaterales (media: 79,66%) siendo estadísticamente significativo (p = 0,023). Prueba de percepción verbal en ambiente ruidoso: implantes simultáneos y secuenciales con corto periodo entre implante (media: 77,17%) frente a los implantes secuenciales con largo periodo entre implantes y los unilaterales (media: 69,32%) siendo estadísticamente significativo (p = 0,002).

**Conclusiones**: Los implantados simultáneamente y los secuenciales de corto periodo adquirieron las ventajas de la binauralidad.

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**Introduction and Objectives**

Clinical experience and research have shown that a cochlear implant (CI) is an effective and safe treatment in severe to profound sensorineural hearing loss, providing functional hearing in children, as well as good levels of language comprehension and acquisition thereof.

Due to an increase in the provision and demand for CI, the last decade has witnessed a growing interest in bilateral implantation aimed at obtaining the benefits offered by binaurality and bilaterality. Numerous studies have shown benefits such as improved sound localisation, improved perception of speech in silence, improved perception of speech with background noise, stimulation of both auditory pathways, assurance of implanting the best ear and development and improvement of language in children.

An absence of these conditions may entail an influence on the central organisation mechanisms of binaural perception. What would happen with unilateral implant users after a second implant? Would they be able to acquire the binaural effect? When should the second implant be considered? Is the interval between both implants relevant?

The aim of this study was to examine the binaural effect among cases of bilateral cochlear implant (with a minimum processor usage of 12 months) in silent and noisy environments, as well as to analyse the differences found between children with: (a) simultaneous implantation (SI) (i.e. in the same procedure), (b) sequential implantation, (i.e. in separate procedures) with a short interimplant period (SIP), of less than 12 months, (c) sequential implantation with a long interimplant period (LIP), of more than 12 months, and (d) unilateral implants.

**Materials and Methods**

We included 90 patients who were implanted at an age between 1 and 2 years (first surgery), between 2000 and 2008, all of them carriers of a Nucleus® Freedom™ model CI and users of speech processors for a period longer than 12 months.

A total of 25 children were unilateral users and 65 were bilateral. Of the latter, 17 were implanted simultaneously, 29 were implanted sequentially with the second implant being performed before 1 year (SIP), and 19 were implanted sequentially with the second implant being performed more than 1 year after the first surgery (LIP).

All patients underwent the following tests:

- Verbal perception test of disyllable words adapted to the age, in a free field, without lip reading, at 65 dB, under silent conditions.
- Verbal perception test of disyllable words adapted to the age, in a free field, without lip reading, at 65 dB, with a signal/noise ratio of 5 dB noise above the signal.
- Sequentially implanted patients underwent a free field tone audiometry to assess the summation effect (the value was given by the arithmetic mean of frequencies 500, 1000, 2000, 3000 and 4000 Hz).

All the tests were performed within soundproofed audiometric booths with loudspeakers at 0° azimuth. We analysed
Table 1  Age at Implantation in Months.

<table>
<thead>
<tr>
<th>Type of implantation</th>
<th>First CI</th>
<th>Second CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilateral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>17.44</td>
<td>28.55</td>
</tr>
<tr>
<td>SD</td>
<td>3.60</td>
<td>3.93</td>
</tr>
<tr>
<td>Bilateral sequential SIP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>19.00</td>
<td>41.00</td>
</tr>
<tr>
<td>SD</td>
<td>2.94</td>
<td>2.93</td>
</tr>
<tr>
<td>Bilateral simultaneous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>16.76</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>3.35</td>
<td></td>
</tr>
</tbody>
</table>

CI, cochlear implant; LIP, long interimplant period; SD, standard deviation; SIP, short interimplant period.

each ear individually, as well as the combination of both in order to assess the binaural effect.

Statistical Analysis

In order to carry out the comparison of mean proportions of correct speech perception tests, patients were divided into 2 groups: the first group consisted of the simultaneously implanted patients together with the sequentially implanted patients with a short period between both implants, whilst the second group consisted of the sequentially implanted patients with a long period between both implants and the unilaterally implanted patients. We used the Student t-test for independent samples in the comparison of means of both groups. We also used the Student t-test for independent samples in order to compare the mean tone threshold values of bilaterally and sequentially implanted groups (short period between implants versus long period between implants) with the first implant, the second implant and both simultaneously. A P value below .05 was accepted as statistically significant.

Results

Implantation Age of Each Group

Table 1 shows the mean ages of implantation in months of each of the study groups, along with their standard deviation (SD).

Speech Perception Test in Silence

The mean ratio of correct responses in the speech perception in silence test was 79.40% among the unilaterally implanted group, 88.24% among the bilaterally and simultaneously implanted group, 82.59% among the sequentially implanted group with an interval less than 1 year between the first and the second implantation when using both implants, and in the case of those with over 1 year interval between both implantations it was 80.00%. The box plot in Fig. 1 shows the percentage distribution of correct responses in the speech perception in silence test of the members of the different groups. The results of patients in the sequential implantation groups were divided according to the device in use (the first cochlear implant, the second implant and both simultaneously). The differences between the means in the verbal perception in silence test were statistically significant (P=.023) when comparing the results grouped by simultaneous and sequential implants with a short period between implants (mean: 84.67%) versus unilateral and sequential implants with a long period between implants (mean: 79.66%).

Speech Perception Test With Noise

The mean ratio of correct responses in the speech perception with noise test was 68.20% among the unilaterally implanted group, 82.35% among the bilaterally and simultaneously implanted group, 74.14% among the sequentially implanted group with an interval less than 1 year between the first and the second implantation when using both implants, and in the case of those with over 1 year interval between both implantations it was 70.79%. The box plot in Fig. 2 shows the percentage distribution of correct responses in the speech perception with noise test of the members of the different groups. The results of patients in the sequential implantation groups were divided according to the device in use (the first cochlear implant, the second implant and both simultaneously). The differences between the means in the verbal perception with noise test were statistically significant (P=.002) when comparing the results grouped by simultaneous and sequential implants with a short period between implants (mean: 77.17%) versus unilateral and sequential implants with a long period between implants (mean: 69.32%).

Comparison of Mean Tone Thresholds Among Bilateral and Sequential Implant Groups

The mean tone threshold among the group with bilateral and sequential cochlear implants with an interval less than 1 year was 25 dB (27.07 using only the first implant and 31.72 dB using only the second implant) versus 26.32 dB (29.21 dB using only the first implant and 35.26 dB using only the second implant) among the group with bilateral and sequential cochlear implants with an interval over 1 year between implants. These differences were not statistically significant. Table 2 shows the mean tone thresholds, along with their SD, of the bilateral and sequential cochlear implant groups, divided by the device in use.

Discussion

Although the human cochlea is fully developed at the time of birth, the auditory system is still immature and completes its development during the postnatal period. The cerebral cortex undergoes a massive reorganisation of dendritic trees during the second and fourth years of life.10,11 This development experiences its maximum plasticity at the age of 3.5 years, approximately,12 and subsequently declines in the
following years. Therefore, the greatest neural plasticity of the auditory system is found during this period. Children who are deprived of auditory impulses for long periods of time undergo a "cross-modal" reorganisation, whereby the visual area is preferentially activated, thus limiting the adaptation of the cortex to afferent impulses from the auditory system such as those from cochlear implants.\textsuperscript{13,14} Lee et al. considered that the period of sensitivity to such changes ended at around 7 years of age.\textsuperscript{15}

Bilaterality is understood as the ability to use the "best" ear in each circumstance.\textsuperscript{16} It is not dependent on a central processing. Binaurality refers to the ability of the brain to simultaneously analyse and process signals from 2 sources, which are then integrated at a central level and allow us to extract and use information from the environment.

The concept of signal to noise ratio (SNR) is very important and refers to the difference in decibels between a given signal and any interfering noise, whether accidental or intentional.

The benefit of binaural hearing for the intelligibility of conversations in noisy environments has long been established in subjects with normal hearing. The factors contributing to the capacity to separate signal from noise are numerous and complex, but there are 3 specific components of bilateral hearing which are particularly involved in the process:

1. Head shadow effect: when the signal and noise are emitted by different sources separated in space, the SNR at each ear is different. This is due, on the one hand, to the different filtering of sounds and, on the other hand, to the physical presence of the head. It mainly affects high frequencies (>1500 Hz) due to their shorter wavelength as compared with the size of the head and produces an attenuation of about 20 dB for high frequencies and 3–6 dB for low frequencies. When both ears are working correctly, a person can "favour" the ear with the most favourable SNR (e.g., the ear opposite to the noise).\textsuperscript{17} It is important to be familiar with the head-related transfer function (HRTF) or acoustic response thereof, which refers to the way in which the head, the ear and the external auditory canal alter

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**Figure 1** Distribution of the percentage of verbal discrimination during silence among the various implantation groups depending on the device in use.

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**Table 2** Mean Tone Thresholds of Bilateral Sequential Implants Depending on the Device in Use.

<table>
<thead>
<tr>
<th>Type of implantation</th>
<th>First CI</th>
<th>Second CI</th>
<th>Both CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bilateral sequential SIP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>27.07</td>
<td>31.72</td>
<td>25.00</td>
</tr>
<tr>
<td>SD</td>
<td>8.61</td>
<td>8.27</td>
<td>8.02</td>
</tr>
<tr>
<td><strong>Bilateral sequential LIP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>29.21</td>
<td>35.26</td>
<td>26.32</td>
</tr>
<tr>
<td>SD</td>
<td>6.72</td>
<td>7.36</td>
<td>6.63</td>
</tr>
</tbody>
</table>

CI, cochlear implant; LIP, long interimplant period; SD, standard deviation; SIP, short interimplant period.
the characteristics of sounds. Hence, through the effect of the head, a sound whose spectrum is flat in a speaker is transformed into another whose spectrum is not flat at the level of the tympanum.

2. Binaural squelch or binaural unmasking effect: whenever there is a sound input through both ears, the auditory system may combine the information to provide a better representation than that which would available if there was only a monaural input. This is the result of processing the differences in time and amplitude and spectral differences between both ears at the central nuclei.\(^{18}\)

3. Binaural redundancy or summation effect: this is thought to occur when the signal and noise come from the same location. Binaural redundancy refers to the capacity of the auditory system to advantageously combine a duplicate representation of the same signal at both ears.\(^{17}\) This summation effect increases sensitivity for small differences in volume and frequency in a particular sound, enabling a better understanding of language, both in silent and in noisy environments.\(^{2}\)

A study by Bronkhorst and Plomp had demonstrated that the combination of the silencing and shadow effects could improve speech discrimination by up to 40% in subjects with normal hearing.\(^{19}\) Moreover, the central binaural silencing effect may increase by a mean value of up to 26% in subjects with normal hearing and up to 19% in subjects with hearing impairments.

The results of the perception in silence test showed that there was a significant binaural effect in silent conditions when comparing groups which had been able to acquire binaurality (subjects with bilateral simultaneous cochlear implants and with sequential with a short period between implants) versus those who were not able to acquire it (subjects with unilateral cochlear implants and with sequential with a long period between implants). In addition, we must note that sequential patients showed a better discrimination when using only the first implant than when using only the second. This seems to highlight the importance of limiting sensory deprivation of auditory systems to the shortest possible period, as well as the benefit of early stimulation.

The results were different when analysing the results in noisy environments. There was a significant improvement in the perception of words when comparing subjects implanted simultaneously and sequentially with SIP versus those implanted unilaterally and sequentially with LIP. The effect of the binaurality achieved by patients with simultaneous implants and sequential with SIP became evident, with statistically significant differences. When perceiving

![Figure 2](image-url) Distribution of the percentage of verbal discrimination with noise among the various implantation groups depending on the device in use.
the signal symmetrically in the cabins, since the speaker was located at 0 degrees, the SNR was similar in both ears, thus minimising the contribution of the shadow effect. This indicates that the differences found were due to the binaural silencing effect and the binaural summation effect. Our results do not agree with those offered by Kühn-İnacker et al., who had reported that the period between the 2 implants did not seem to be a factor which could influence the results of discrimination in noisy environments, although it did influence the level of speech rehabilitation required after surgery. They believed that it could be secondary to the heterogeneous nature of the sample and to the need for tests which simulated the conditions of the daily lives of children more realistically. Therefore, they took into account that the improvement and reduced rehabilitation time were closer to the real conditions, since these had a longer follow-up than tests which were conducted only once.9

We observed a summation effect (not related with binaural summation) of 2–3 dB when using both implants compared with the best unilateral threshold in both sequentially implanted groups. This summation effect was due to the condition of bilaterality (we were only measuring a single response). Therefore, the effect of the time period elapsed between both implants did not influence the results.

Moreover, it is important to remember the added difficulty in performing the tests and obtaining ideal results when working with children.

Conclusions

Bilateral CI in children performed simultaneously and sequentially with a short period between the placement of both implants enables the acquisition of binaurality and its advantages. Subjects implanted sequentially with a long period between both implants will benefit from bilaterality, but without evidence of the development or acquisition of functions related to binaurality.

The reported findings would require studies with greater numbers of patients to confirm the results.

Conflict of Interests

The authors have no conflict of interests to declare.

References