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Prospective Long-term Auditory Results of Cochlear Implantation in Prelinguistically Deafened Children: The Importance of Early Implantation

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The objectives of this study were to report the long-term auditory results of prelinguistically deafened children with bilateral profound hearing impairment treated with a cochlear implant (CI); to analyze the role of auditory stimulation in the development of communicating abilities in early implanted children; and to define the limits of the auditory critical period. It was designed as a prospective cohort single-subject repeated-measures study of children with bilateral profound hearing impairment treated with a CI at a tertiary referral center with a pediatric CI program since 1991. A total of 182 children with bilateral prelinguistic hearing impairment of profound degree treated with a Nucleus CI were enrolled in the study. Eighty-six children received a Nucleus 22 CI and 74 received a Nucleus 24. For data analyses the children were categorized by ages: 0–3 years of age ($n = 94$); 4–6 years ($n = 36$); 7–10 years ($n = 30$); 11–14 years ($n = 22$). The children were evaluated with a protocol that included tests of audition and speech perception, with closed-set (Vowel Confusion test, Series of Daily Words) and open-set tests (e.g. bisyllables, CID Sentences, CID Sentences adapted for children). Pure-tone averages significantly improved for all children in all groups with the CI compared with preoperative values. Nevertheless, only children implanted before the age of 6 years developed a high ability for recognition of bisyllables and sentences in an open-set. Results show that the earlier the implantation is undertaken, the better the performance outcome. Children implanted outside of the auditory critical period demonstrated significantly poorer performance, suggesting the occurrence of irreversible changes in the central auditory system. In conclusion, eligible children should receive a CI as soon as bilateral profound hearing impairment is diagnosed. This usually permits them to achieve high-performance levels on speech and language measures and potentially integration into an oral communication environment. *Key words: auditory critical period, hearing impairment, inner ear surgery, neural plasticity, treatment outcome.*

INTRODUCTION

Clinical experiences, particularly in the last 10 years, have shown the importance of early implantation in order to take advantage of the higher degree of auditory plasticity in infancy. Cochlear implantation is currently one of the possible choices for the rehabilitation of profound sensorineural hearing impairment in children, regardless of a prelinguistic or postlinguistic onset (1–6). It has also been shown that early implantation is technically possible without increasing the occurrence of complications (7–12).

In addition, technical advances such as neural response telemetry have greatly facilitated the program of speech processors for non-cooperative patients, especially in the case of children under the age of 2 years (13). These and other aspects will be addressed in this paper, following the experience in our cochlear implant program with more than 400 implantees since 1989, two-thirds of whom are pediatric patients.

METHODOLOGY

Patients

A prospective study was undertaken in a consecutively implanted group of 182 congenitally or prelinguistically deaf children. Prelinguistic hearing impairment is defined as that occurring before the age of 2 years. The children were grouped by age at implantation: group 1: 0–3 years ($n = 94$); group 2: 4–6 years ($n = 36$); group 3: 7–10 years ($n = 30$); and group 4: 11–14 years ($n = 22$). Demographic and relevant data for the groups are shown in Table I. In addition, as indicated in the results, subgroups of children from groups 1 and 2 will be studied further separately.

Preoperative evaluation

All children were evaluated according to a preoperative protocol that consisted of the following. (i) History, physical and otorhinolaryngological examination. (ii) Neuropediatric examination and family evaluation. Psychological assessment was completed to evaluate the children's cognitive abilities, and to rule out patients with other neurological conditions that may compromise postoperative performance. (iii) Auditory evaluation and speech perception testing (see further). (iv) Auditory brainstem responses (ABRs): ABRs were recorded, at least twice, in all infants and children before surgery. To determine the auditory threshold, the wave V latency was evaluated at consecutive intensities of stimulation up to 120 dB. (v) High-resolution computed tomography (HRCT) of the temporal bones. (vi) Counseling and informed consent: parents and older patients were extensively informed of the potential advantages, disadvantages and risks associated with implantation to establish

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realistic expectations of postoperative performance. Children were included in the informed consent process to the extent of their ability.

Evaluation of audition, speech perception and production

Patients underwent an audiological evaluation before and after implantation according to a protocol developed for the Spanish speaking population (14). This protocol includes pure-tone audiometry and speech perception tests. In younger children, visual reinforcement audiometric techniques were used for the evaluation of tonal thresholds. All speech perception tests were performed in the Spanish language, adapted or self-developed, and were administered in the sound-field, via female live-voice at levels of 65 dB HL in sound-treated booths without visual support and without repeat. The closed-set test used was the Vowel Confusion test ('cVc' paradigm: e.g. bAs, bEs, bOs, bIs, bUs). Open-set lists of bisyllabic words were also used (e.g. 'mesa', 'hojas', 'lápiz', 'cama').

Speech production and language were evaluated via the Peabody Picture Vocabulary test and the Reynell's general oral scale, both adapted for the Spanish language (15, 16). Results on these tests are expressed in terms of developmental language age in years and months and compared with the child's chronological age. All tests were administered preoperatively, 1 year postoperatively and annually thereafter. As the children's abilities evolved with increasing age and use of the device, more difficult tests were administered along the follow-up period as appropriate.

Candidacy and inclusion criteria

All children included in the study met the following criteria: (i) prelinguistic profound bilateral hearing impairment, with pure-tone average (PTA) and ABR thresholds > 91 dB HL, in both ears; (ii) no associated handicapping condition; and (iii) the absence of any medical contraindication for surgery.

Surgical issues

All children underwent a standard surgical cochlear implantation, including an extended endaural or retroauricular incision, mastoidectomy, and promontorial cochleostomy. Surgery for implantation in very young children differs for some steps relative to that used in older children or adults. These differences are related to anatomical variations of the middle ear and cranium during infancy, which are overcome through the introduction of minor changes in the surgical technique (17). The changes implemented are mainly related to the incision and the formation of the bony-bed for the receiver-stimulator.

Intra-operative device monitoring methods used regularly and standard plain X-rays were carried out routinely and more recently as described; electrically evoked brainstem responses with Neural Response Telemetry (NRT™) were also used (18). Complications were recorded and assessed following the classification by Hoffman and Cohen (19).

Device and coding strategy

All children received a multichannel Nucleus™ device (Cochlear Ltd, Australia): either a Nucleus 22 (in 86 patients) or a Nucleus 24 (in 96 patients). Irrespective of the cochlear implant (CI) device in use, the speech processor was programmed using the SPEAK coding strategy. The number of activated electrodes did not significantly vary between the groups regardless of the follow-up time.

(Re)habilitation methods

After the initial fitting and programming, the rehabilitation of most patients followed an auditory-verbal methodology, although some required complementary support – generally involving the use of an acoustic hearing aid in the contralateral ear (bimodal). The educational setting both preoperative and postimplant was in the mainstream school with additional regular sessions of curricular and phono-audiologic support. This educational model is the most commonly encountered in Spain as opposed to special educational facilities for hearing-impaired children.

Database and statistics

Prospectively, results on performance test measures and other items of interest were entered into a common database, analyzed and graphically represented using the SPSS 9.0 statistical package. Statistical comparison of mean values was performed using the Student's t-test for independent samples using a significance criteria of $p < 0.05$.

RESULTS

As it has been previously shown by different authors (1–6), there is a direct correlation between the age at implantation and the results on speech perception, production and language measures for the prelinguistically deafened child population. The results from our prospective study summarize the results over an 8-year follow-up period for the various subgroups of children based on age at implant, as described earlier. Based on our results, we attempt to determine the delineation between fair or poor performers versus good performers based on age at implant, i.e. the upper limit of the so-called auditory critical period.

Auditory results

Pure-tone audiometry. There were no significant differences among pre-implantation PTA thresholds in the studied frequencies (0.5–4 kHz) in the four groups of prelinguistically deafened children. After the activation of the CI, the PTA significantly improved in all groups of children, showing a clear improvement in sound detection of frequencies in the speech spectrum at conversational levels. Postoperatively, mean PTA thresholds ranged from 32 to 44 dB HL, and did not significantly change up to the eighth year of follow-up (Fig. 1).

Speech perception closed-set test. Figure 2 shows the results achieved in the Vowel Confusion test. As shown, all groups of children were able to identify vowel phonemes in a closed-set context. Children in groups 1 and 2 performed significantly better than the other groups, regardless of follow-up time. Children below 6 years of age continued to demonstrate progress throughout the follow-up time, with a more rapid rate of improvement noted for children implanted below 3 years of age. The children in group 1 achieved mean performance levels of 90% or greater from the second follow-up year onwards. Interestingly, the results of group 1 were better than those for group 2 in the Vowel Confusion test from the first to the eighth year of follow-up ($p < 0.05$). Of emphasis is the consistency of the results for group 1, with only small standard deviations, especially as the time of follow-up increases.

Speech perception open-set test. Figure 3 shows the results achieved for the Bisyllabic Words test. This test is more demanding because it is given as an open-set without visual support. Given the intrinsic test difficulty for children developing their speech abilities, this test could not be administered to all younger children in the first years of follow-up. Children implanted below 6 years of age (groups 1 and 2) performed significantly better ($p < 0.05$) than children implanted above 6 years (groups 3 and 4), regardless of follow-up time.

Children in group 1 demonstrated a more rapid improvement over time, performing significantly better ($p < 0.05$) than children in group 2 throughout the follow-up interval. From the second postoperative year onwards, children in group 1 demonstrated the ability to recognize bisyllabic words and sentences presented in an open-set, with mean performance over 85% and 90% at the fourth and eighth years of follow-up, respectively. Children in group 2 achieved a maximum mean performance of 60% at the sixth year of follow-up. Once again, children in group 1 had consistent results with small standard deviations decreasing with time.

Results of the Bisyllabic Words test in children over 6 years of age (groups 3 and 4) remained below 20%, in some cases even after 8 years of implantation. In these cases, visual support is required to comprehend open-set speech. There were no significant differences in performance among these three groups of children, regardless of their age at implantation.

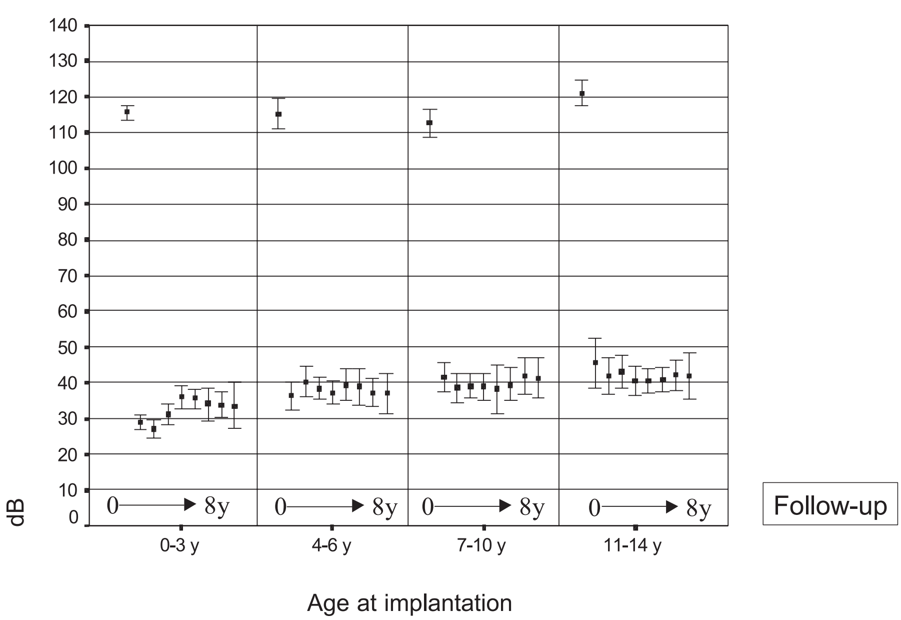

Fig. 1. Mean pure-tone thresholds versus age at implant. Data show the mean pure-tone average (PTA) from thresholds at 0.5, 1, 2, and 4 kHz (±2 standard deviations) per age group per test interval, including preoperatively and annually postoperatively up to the eighth year of follow-up. Groups of children from left to right: 0–3 years ($n = 94$); 4–6 years ($n = 36$); 7–10 years ($n = 30$); and 11–14 years ($n = 22$).

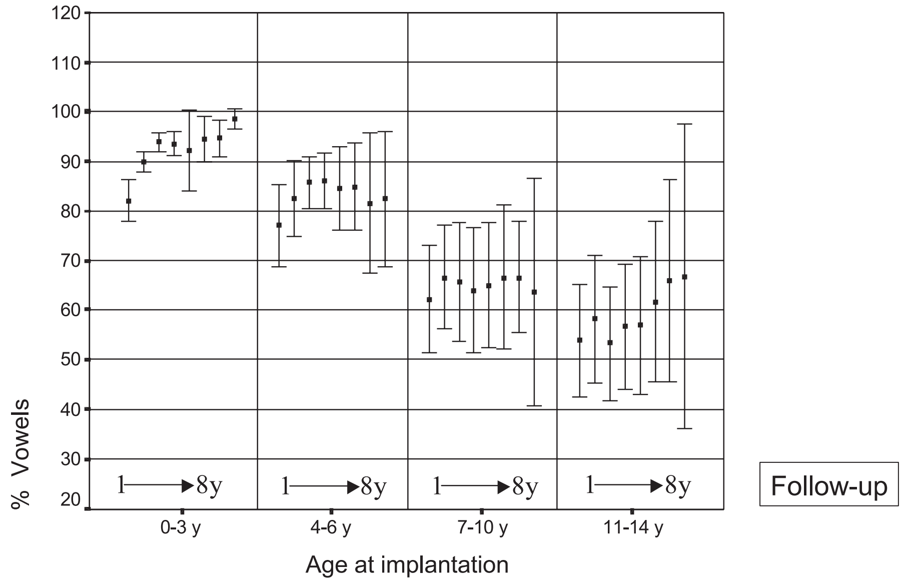

Fig. 2. Closed-set Vowel Identification versus age at implant. Data illustrate mean values (+2 standard deviations) per group per postoperative annual interval, including the eighth year of follow-up. Groups of children from left to right: 0–3 years ($n = 94$); 4–6 years ($n = 36$); 7–10 years ($n = 30$); and 11–14 years ($n = 22$).

Effect of age at implant upon results (1–5 years of age). The results obtained once again showed the significant influence of age at implantation on performance. There is a clear point of inflexion when comparing results from groups 2 and 3, supporting the existence of an auditory critical period that comprises the first 6 years of life. Nevertheless, the presence of significant differences in performance between groups 1 and 2 suggests that age at implant is an additional crucial factor within this period of neural plasticity.

In order to detect possible differences, we analyzed the performance in bisyllabic words versus the age of implantation in congenitally hearing-impaired children treated with a CI before 6 years of age. A total of 126 children were grouped by age at implantation: the first group, 0–1 years ($n = 37$); the second group, 2–3 years ($n = 63$); and the third group, 4–5 years ($n = 26$).

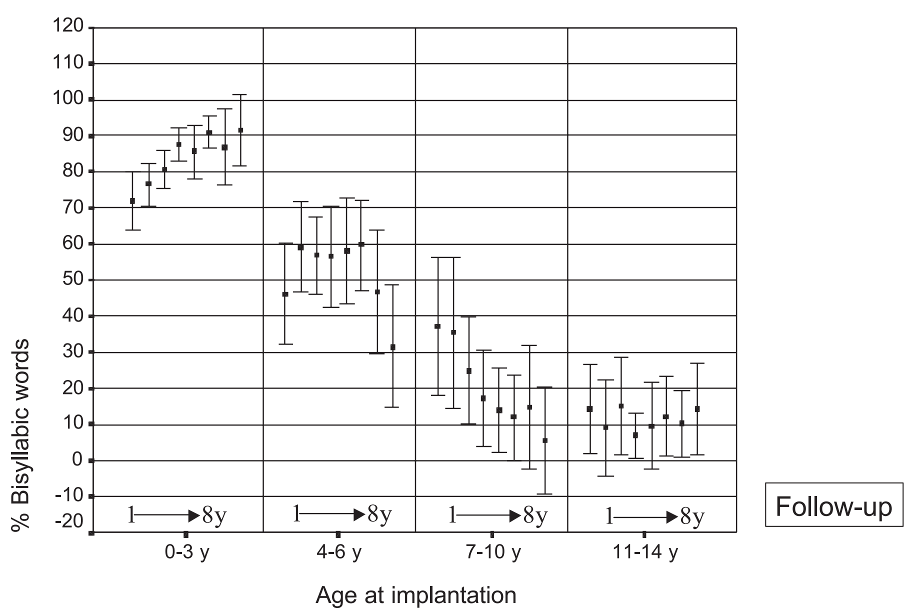

Fig. 3. Open-set bisyllabic word recognition versus age at implant. Data illustrate mean values (+2 standard deviations) per group per annual postoperative interval, including the eighth year of follow-up. Groups of children from left to right: 0–3 years ($n = 94$); 4–6 years ($n = 36$); 7–10 years ($n = 30$); and 11–14 years ($n = 22$).

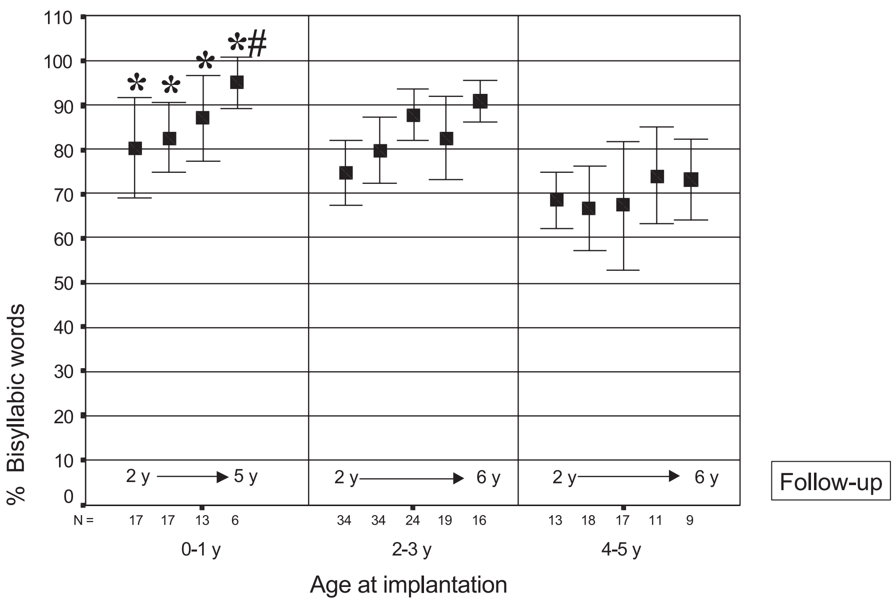

Fig. 4. Open-set bisyllabic word recognition versus age at implant (0–5 years). Data illustrate mean values (+2 standard deviations) per subgroup per postoperative interval from the second year to the fifth or sixth year of follow-up. Groups of children from left to right: 0–1 years; 2–3 years; and 4–5 years. *Statistically significant differences between children implanted before 2 years old and children implanted between 4 and 5 years of age ($p < 0.05$). #Statistically significant differences between children implanted before 2 years and children implanted between 2 and 3 years of age in the fifth year of follow-up ($p < 0.05$).

The Bisyllabic Words test results were slightly better for children implanted before 2 years of age. Results were statistically significant in the fifth year of follow-up compared with children implanted between 2 and 3 years of age, and throughout the follow-up interval compared with children implanted between 4 and 5 years of age (Fig. 4).

Speech production results

Figure 5 shows the correlation of chronological age with the age of acquisition of vocabulary as determined by the Peabody Vocabulary test. The correlation for the population of normal hearers is displayed via the diagonal discontinuous line. Children implanted between 0 and 3 years of age followed an almost normal acquisition of vocabulary, whereas children from 4 to 6 years of age showed a negative deviation of approximately 3 years compared with the normal baseline, whilst children implanted from 7 to 10 years of age showed a negative deviation of more than 4 years.

Figure 6 demonstrates the results from the Reynell oral language scale plotted as chronological age versus the age developmental language age. Once again the

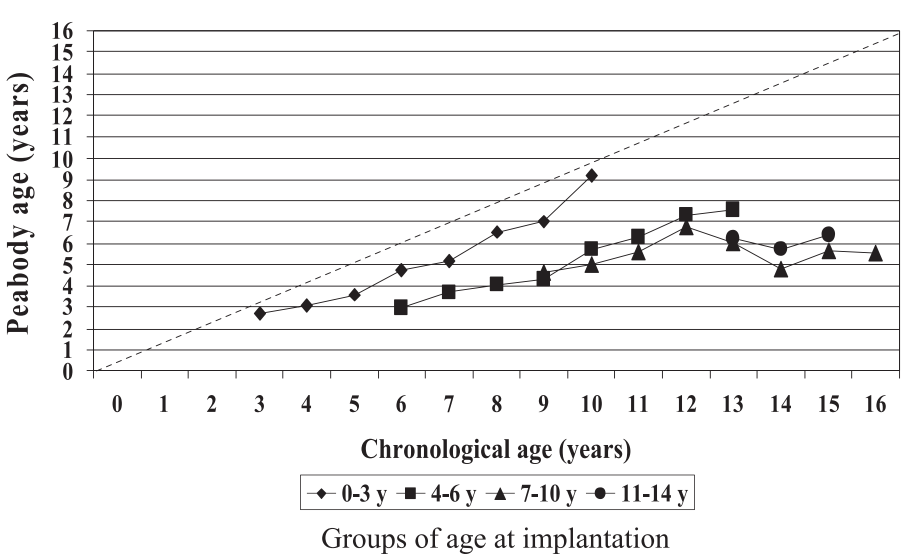

Fig. 5. Performance on the Peabody Vocabulary test. Data show the mean vocabulary age versus the chronological age per group per annual postoperative test interval up to the eighth year of follow-up. Groups of children from left to right: 0–3 years; 4–6 years; 7–10 years; and 11–14 years. Dotted line shows data for a population of normal hearing subjects.

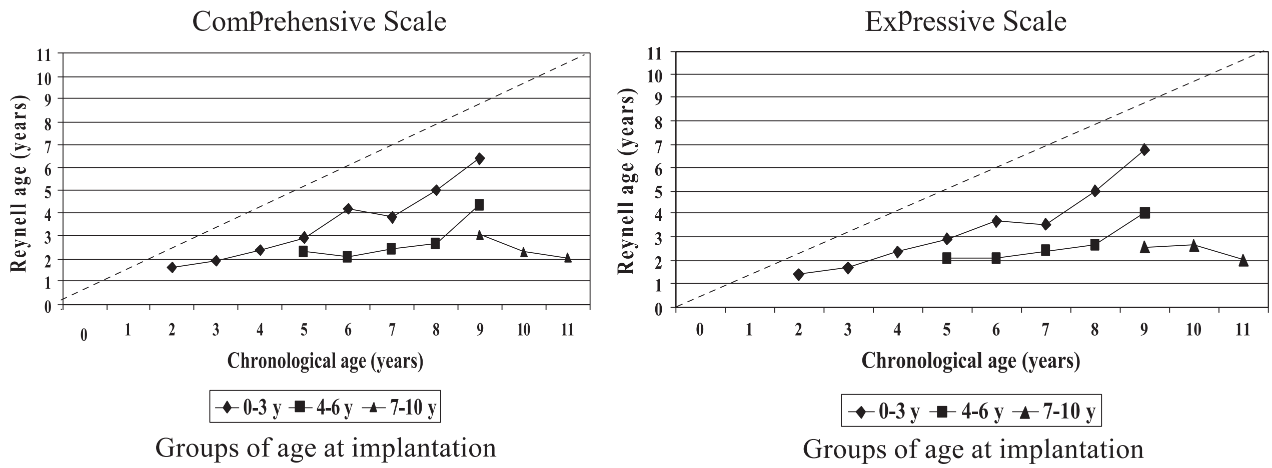

Fig. 6. Performance on the Reynell General Language scales. Data show the mean performance age versus the chronological age for comprehensive and expressive language separately. Groups of children from left to right: 0–3 years; 4–6 years; and 7–10 years. Dotted line shows data for a population of normal hearing subjects.

results for the population of normally hearing children is illustrated via the diagonal discontinuous line. Children implanted between 0 and 3 years of age showed a negative deviation of approximately 2 years relative to the normal population, whereas children implanted between 4 and 6 years and 7 and 10 years showed a negative deviation of more than 4 years with a much flatter gradient, suggesting a slower rate of progress over time.

Complications

Complications were recorded as they occurred according to the Hoffman and Cohen classification (19). Of specific interest was the analysis of the percentage of complications versus age at implant, to determine the effect of age upon complications and contraindication to early implant.

Complications, recorded from our pediatric implant population, were analyzed for two groups of children: those implanted before 2 years of age and those implanted between 2 and 5 years of age. No major complications were reported for children implanted before 2 years of age during the first 5 years of postoperative follow-up. In contrast, four major complications were noted for the group of children implanted from 2 to 5 years of age. One report was related to the ulceration of the cutaneous flap over the receptor-stimulator that required revision surgery. The remaining three major complications related to complete CI failure requiring reimplant in all cases. These complications occurred in the first 3 years of postoperative follow-up with a mean time of occurrence of 1.2 years postimplant. Irrespective of age at implant there were no cases of meningitis, facial palsy, electrode array emigration, or any other major complication.

DISCUSSION

Although all subjects had similar pure-tone thresholds after surgery, major differences were observed between the groups for performance on speech recognition measures, especially when presented in an open-set. As shown in Figs. 2 and 3, consistent relative differences are noted between the groups for both closed and open-set speech perception measures. Throughout the follow-up interval children implanted before the age of 3 (group 1) consistently demonstrated statistically better performance compared with all children implanted later. Prelinguistically deafened children implanted between 4 and 6 years of age (group 2) scored significantly better than children implanted after the age of 6 years (groups 3 and 4). No significant difference was noted in performance for children implanted above the age of 6 regardless of the age at implant. The same relative differences between the groups for performance in tests of vocabulary acquistion and expressive and comprehensive language were noted, as measured via the Peabody and Reynell scales respectively (Figs. 5 and 6).

As all patients enrolled into this prospective study had normal cochleae and all patients underwent similar surgical procedures resulting in similar electrode insertion lengths, the differences in performance observed between the groups cannot be attributed to other potentially influencing factors such as anatomical, surgical or technical specifics (Table 1). Similarly, all children used the same coding strategy. Finally, all children were programmed and followed by the same team, who were also involved in the rehabilitation and educational models. Although some variability in educational placement and rehabilitation services available is present in different regions in Spain, these models are based upon oral stimulation as the main

Table 1. *Demographics*

Groups	Mean age at implantation (years)	Sex	Etiology		PTA pre CI (dB HL)	Insertion length (mm)
			Known	Unknown		
Group 1 (0–3 years)	1.79 ± 0.73 σ	M = 40 F = 54	50%	50%	118.53 ± 9.58 σ	22.62 ± 2.13 σ
Group 2 (4–6 years)	4.95 ± 0.89 σ	M = 23 F = 13	63%	37%	116.37 ± 12.36 σ	21.86 ± 2.40 σ
Group 3 (7–10 years)	8.60 ± 1.04 σ	M = 17 F = 13	52%	48%	115.81 ± 7.47 σ	22.17 ± 2.58 σ
Group 4 (11–14 years)	12.32 ± 1.04 σ	M = 10 F = 12	89%	11%	122.33 ± 7.36 σ	22.95 ± 1.69 σ

mode of communication and in integration of the hearing-impaired child into the mainstream educational system.

Our results are in accordance with those from other authors who have reported better performance of children implanted before 5–6 years of age (1–6). However, this in no way implies that there is a cut-off age for implantation following that time. In fact, as experienced in the course of our own cochlear implant program, successful treatment with a cochlear implant in children above the age of 6 years suffering from a profound prelinguistic deafness has been demonstrated via the presence of measurable benefit on outcome measures postoperatively (5). These patients also clearly benefit from their cochlear implant in variety of ways: (i) improved environmental sound detection; (ii) improved perception of supra-segmental speech characteristics (intonation, rhythm, pitch, intensity); (iii) improved speech articulation (thus are better understood); (iv) increased lip-reading ability; and (v) open-set speech recognition to a limited degree (some attaining telephone use). Generally speaking, for late implanted prelinguistically deafened patients, better results arise from those who have demonstrated good oral language and comprehensive reading skills, good lip-reading skills and some residual hearing that permitted the use of hearing aids preoperatively. These factors are important considerations when counseling the patient preoperatively and influences the patient's expectations of the potential outcomes (20).

Recent studies (6–12) have shown that it is possible to undergo cochlear implantation before 2 or 3 years of age, leading to highly satisfactory performance without increasing complication rates relative to that incurred with older children. These reports, together with our data (Fig. 4), show once again, that higher levels of performance are attained at a faster rate by the early implanted children. This point emphasizes the importance of universal hearing screening in the pediatric population and early intervention in cases of hearing impairment. The excellent results achieved by children implanted under the age of 3 years provide the subsequent foundation of skills for these infants to be fully and satisfactorily integrated into an oral social environment.

In our study, the number and severity of complications in the group of children implanted before 2 years of age was actually lower than that for children implanted between 2 and 5 years. Our data confirm that it is possible to decrease the age of implantation without increasing risks and complications, provided a team of competent anesthesiologists, surgeons, and audiologists is available to deal with such a young population of patients.

The significantly better performance over time observed for children implanted within the youngest age group can be related to the higher degree and hence relative increased capacity of the existing neural auditory plasticity. During this period of time, the central auditory system (CAS) has the ability to modify the developmental connection patterns based on environmental stimuli. Although with some exceptions, the absence of progression of performance on open-set tests for children implanted after 5 years of age, with continuous stimulation for 8 years, clinically demonstrates the limits of the critical auditory period.

The auditory critical period corresponds with a period when storage of natural stimuli would be facilitated by a certain pre-organization of the receiving brain areas (21). Although neuronal emigration in the primary auditory cortex and development of axonal layers occurs within the first 4–5 years of life (22, 23), it remains unclear what the role of neural activity is in the development and plasticity of periphery-related afferent patterning in the brainstem and cortex (24). Upon initial activation of a CI in children (before chronic stimulation), electrically evoked auditory waveforms can be obtained (25), suggesting that auditory midbrain function is to some degree maintained during potentially critical periods in development.

Experimental auditory deafferentation also supports the existence of an auditory critical period. Several reports have demonstrated peripheral auditory deafferentation in neonatal specimens that induces the death of 25–50% CN neurons, depending on the timing of the deafferentation (26–29). Early electrical stimulation after deafferentation is capable of preventing these changes within the CN (30), and may avoid the modifications in the organization of the CAS. These changes are not reversible in later stages, even though electrical stimulation is provided.

Moreover, recent studies based on cortical auditory evoked potentials carried out in implanted children show that after 6 months of afferent stimulation through the CI, the P1 cortical evoked potential evidences normal latencies in children who experienced less than 3.5 years of auditory deprivation (31). Prolongation of the latency of the P1 is well correlated with the period of hearing deprivation before surgery, as shown in early implanted children (32). A PET-scan study (33) shows that whenever the CAS is not provided with auditory inputs in the early years of life, a cross-modal plasticity phenomenon leads the auditory cortex to respond to visual stimuli. This concept of cross-modal plasticity would well explain the reason for the irreversible poor speech discrimination after the auditory critical period has ended, even when a long period of auditory input via the CI and rehabilitation are provided.

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