

# Electric Acoustic Stimulation in Children

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## Abstract

**Background/Aims:** The combined electric acoustic stimulation (EAS) of one ear is a topic that has received considerable attention over the last 10 years, the technique having originally been introduced by Prof. Christoph A. von Ilberg for so-called borderline adult cochlear implant (CI) candidates. Its development has followed several parallel strands, including the modification of existing surgical approaches and the use of different CI devices (including new designs of electrode), as well as having been applied to various different groups of patients. The aim of the study described herein was to investigate the application of EAS in children with partial deafness (PD). **Methods:** In 2002, we performed the first implantation of an adult patient with PD, in which we pioneered the technique of partial deafness cochlear implantation (PDCI). Encouraged by the outstanding results achieved by the application of EAS in adults, we have extended its application to children who have a significant amount of residual hearing in the ear selected for implantation. Between September 2004 and December 2007, 15 children with PD and 10 platinum hearing aid users were implanted with either a COMBI 40+ or a PULSAR, using the 'round window' technique to increase the probability of hearing preservation. **Results:** Monosyllabic word recognition increased over a 12-month period in the platinum group, from 31 to 60% under quiet conditions and from 1 to 19% under noisy conditions. In the PDCI group, the commensurate increase was from 34 to 67% under quiet conditions and from 7 to 47% under noisy conditions. **Conclusion:** The application of EAS in children gives them the ability to understand speech, hence allowing the child's overall communication skills to be improved by increasing their efficiency and effectiveness.

The primary aim of pediatric cochlear implantation is to provide critical speech information to the child's auditory system and brain, thus improving as far as possible his or her chances of developing spoken language. The amount of speech information available to children with cochlear implants (CIs) is reduced by the limitations of current CI systems, which are characterized by (a) an insufficient number of effective channels imposed by the design and placement of the electrode, leading to poor frequency resolution; (b) a deficiency in the representation of the fine structure of the input signals, and (c) too coarse representation of the fundamental frequencies that are required to interpret complex sounds [1].

As a consequence of these limitations, the speech discrimination results in children with CIs are very much lower than those for children with normal hearing, particularly in demanding situations, such as those in which speech occurs in competition with noise (mainly due to limitation a above) and in competition with other talkers (mainly due to limitation c above) [2].

Furthermore, Eisenberg et al. [3] demonstrated that children with CIs had greater difficulty understanding sentences under noisy conditions than children with moderate-to-severe hearing loss who used hearing aids (HAs). This problem, under both noisy conditions and in the presence

of competing sounds, can reduce the opportunities for incidental learning through overhearing, which are known to play a significant role in child development.

The perception and interpretation of the suprasegmental features of speech, such as intonation, stress, and emphasis, can be significantly impaired in children with CIs (mainly due to limitation c above). Furthermore, Most and Peled [4] found that children with CIs perform significantly less well in stress and intonation tests than children with profound hearing loss who used HAs. Because suprasegmental features are essential for communication, restricted access to them can adversely affect the (re)habilitation process in children with CIs.

In addition, the musical appreciation of children with CIs is poor (mainly due to limitation b above), and this phenomenon can offset the possible advantages of musical training [5]. Musicality and music training in children may have a positive effect on language, cognition, and social development in children. In order to realize the aim of pediatric cochlear implantation by increasing access to speech information, continued efforts must be made to overcome the limitations of CI systems. One possible approach is the application of electric acoustic stimulation (EAS).

### **Possible Advantages of Electric Acoustic Stimulation in Children**

The combined EAS of one ear was first proposed by von Ilberg et al. [6] and later achieved in adults using an HA and a CI in the same ear [7–9] or via the use of natural nonamplified low-frequency hearing and CIs in a group of patients with partial deafness (PD) [10–12]. There are also reports of benefits from EAS that accrued from the application of DUET™ processor, which combines speech processor and HA in one device [13, 14]. EAS in children can make up for the limitations of CI systems (see limitations a–c above) on the basis of

the same mechanisms that underlie the benefits of combined EAS in adults.

By summarizing the detailed discussion of the possible mechanisms involved in EAS presented by Turner et al. [15], Qin and Oxenham [16], and Dorman et al. [17], the following advantages of using EAS in children are apparent:

- (1) acoustic stimulation of the apical region can improve frequency resolution at low frequencies (thus compensating for limitation a above);
- (2) using EAS, fine structure information is presented without modification in the low-frequency range (thus compensating for limitation b above), and
- (3) this fine structure information is likely to include  $F_0$  (thus compensating for limitation c above).

On the basis of the significant body of evidence of the benefits of EAS observed in adults, we believe that the application of EAS in children can considerably enhance their auditory and linguistic experiences and facilitate cognitive and linguistic functioning, thus enabling the child to follow more closely a normal course of development. The use of EAS in children of course requires the implantation of a child with residual hearing, and the preservation of this residual hearing during the surgery. The use of CIs in children with residual hearing is not entirely new because of the changes in the criteria of qualification for this procedure over the last 20 years.

### **Cochlear Implantation in Children with Residual Hearing**

It is generally accepted that CIs may be offered to children who have little potential for speech understanding, due to the limited benefits of acoustic stimulation using a well-fitted HA, although the definition of 'limited benefits' has been altered many times over the last 20 years. Originally, only those children who had very little residual hearing and who showed no demonstration of sound

awareness using HAs were considered to be candidates for cochlear implantation. By assuming a relationship between the degree of residual hearing and the benefit conferred by the use of an HA, a classification of children with sensorineural hearing loss from 'good' to 'poor' HA user was then proposed, based on pure tone average (PTA), using the scale bronze (for PTA >110 dB), silver (for 110 > PTA > 100 dB), and gold (for 100 > PTA > 90 dB) [18]. Gradually, the criteria for implantation have been expanded to include children with better residual hearing, and now include silver and gold HA users. This change in the criteria of qualification was supported by the observation that implanted children in all three classes performed better than their peers who used HAs and had comparable hearing loss. More recently, a platinum HA user group was defined for PTA between 60 and 90 dB [19]. It was shown that hearing in implanted children in the platinum group was better with a CI than with an HA.

Several researchers have reported that children who have some degree of residual hearing before implantation achieved better speech perception skills than those with poorer hearing [20–22]. A degree of residual hearing before implantation can therefore be conducive to successful implantation.

### **Preservation of Hearing after Cochlear Implantation**

#### *Children with Residual Hearing*

The opinion that preservation of any residual hearing must be an aim of all CI surgeries has recently been expressed by authors reporting on the use of EAS in adults [7, 8]. The result of relaxing the qualification criteria that allow increasing numbers of children with residual hearing to be implanted has been to ensure that the preservation of their residual hearing should be taken into consideration. Although the preservation of hearing in adults has been extensively reported

[23–25], publications on this issue in the pediatric literature are few and far between. Skarzynski et al. [26] assessed hearing preservation in 7 children and 19 adults implanted with the COMBI 40+ system and found that only 19% of patients lost all measurable hearing after cochlear implantation. Interestingly, variables such as age and duration of deafness did not influence the preservation of residual hearing in their study. In contrast, Kiefer et al. [27] proposed that children are more likely to retain their residual hearing than adults.

Willingham and Manolidis [28] compared postoperative auditory steady-state response (ASSR) thresholds to preimplant thresholds in a group of 12 children implanted with the MED-EL COMBI 40+ system. There were no statistically significant differences between the pre- and postimplant ASSR thresholds at 250 and 500 Hz, and at 1, 2, 4 and 8 kHz in the implanted ear. The results of their study showed that it is possible to preserve residual hearing in children at a level that is at least no worse than in adults. In order to combine acoustic and electric hearing (using EAS), a sufficiency of residual hearing is required at low frequencies. However, it is still unclear how much residual hearing is sufficient for effective EAS. In studies of combined EAS in adults, James et al. [29, 30] and Frayesse et al. [31] proposed that the criteria for inclusion in conventional candidates for cochlear implantation should be postoperative thresholds of 80 dB (for 125 and 250 Hz) and 90 dB (for 500 Hz), in order that residual hearing could be achieved with a high-power HA. By applying these criteria to children, it may be assumed that those children who are platinum HA users usually possess enough residual hearing to be considered as EAS candidates.

#### *Children with Partial Deafness*

In a recent study, a new group of children with PD, who fell outside of the typical selection criteria, was identified as being potential candidates for EAS. Skarzynski et al. [10] describe PD as being characterized by normal or slightly elevated thresholds at

low frequencies with almost total deafness at higher frequencies. Children in this group remain beyond the scope of effective treatment using HAs alone. Such children had not previously been considered for cochlear implantation, because it was feared that this intervention would damage the functioning part of the cochlea. Encouraged by the outstanding results achieved following partial deafness cochlear implantation (PDCI) in adults, we decided to perform PDCI in children. The first child with PD was implanted at our center in September 2004. To date, there is only one report describing PDCI and EAS in children [32]. The results contained therein demonstrate that some hearing could be preserved in all children with PD, and that furthermore 8 out of 9 children had functional hearing preservation (a rate of 88%). Functional preservation implies that the individuals can be fitted both electrically and acoustically in the same ear, or can use their preserved natural low-frequency hearing to optimize the use of EAS.

## Methods

### Subjects

Between September 2004 and December 2007, 15 children with PD and 10 platinum HA users were implanted with either a COMBI 40+ or a PULSAR, using the 'round window' technique to increase the likelihood of hearing preservation. Results from the first 9 PDCI children have been reported separately [32]. All subjects were implanted in the ear with the worse hearing. The mean age at implantation in the PD group was 9.5 years (ranging from 4.2 to 16.6 years) and in the platinum HA user group the mean age was 9.37 years (ranging from 6.96 to 14.72 years). The reported etiologies were as follows: unknown ( $n = 13$ ), hypoxia ( $n = 5$ ) and ototoxicity ( $n = 7$ ). The PDCI children were implanted using 20-mm partial insertion of a 30-mm-long standard electrode ( $n = 2$ ) as well as full insertion of a 20-mm M-electrode ( $n = 13$ ). A limited insertion depth was used in order not to interfere with the region in the cochlea that is associated with good acoustic low-frequency hearing. The platinum HA users were implanted using full insertion of a standard electrode ( $n = 7$ ) or FLEX electrode ( $n = 3$ ) because they had less low-frequency hearing. All children had at least 1 year of experience of using the device.

### Surgery

The same round window surgical technique [12] was used to ensure hearing preservation in all subjects.

This technique has six main steps:

(1) mastoidotomy;

(2) posterior tympanotomy to allow visualization of the round window niche;

(3) puncturing the inferior part of the round window membrane, thus enabling a direct approach to the scala tympani;

(4) insertion of the electrode array;

(5) fixing the electrode in the round window niche with fibrin glue (the membrane must be left partially uncovered to preserve its mobility), and

(6) fixing the device in a well that is made in the temporal bone.

It may be more difficult to insert the electrode in children than in adults because of the short distance between the facial nerve canal and the annulus fibrocartilagineus of the tympanic membrane. For this reason, an anterior tympanotomy is performed more frequently in children than in adults, in order to improve visualization of the round window niche. It is also necessary to close the mastoid with Spongostan, fibrin glue and a piece of bone obtained during the mastoidectomy.

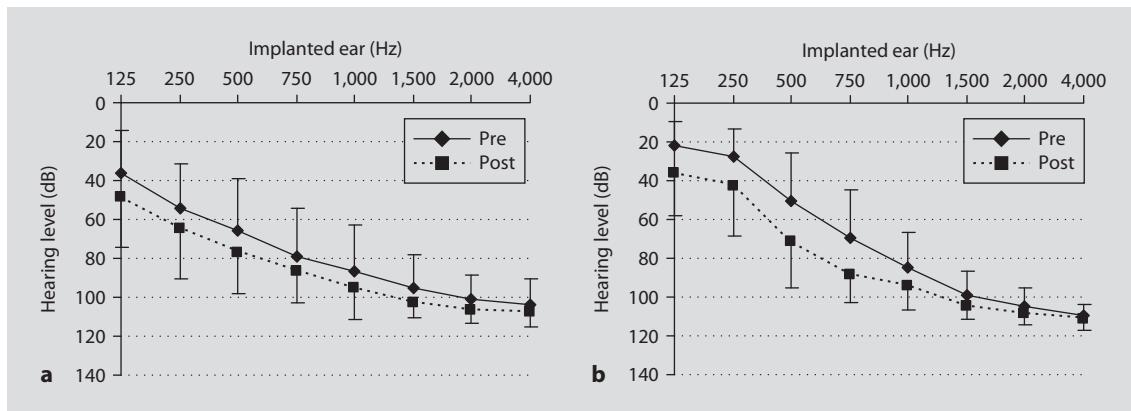
### Programming

The speech processor was programmed in such a way that there was a slight overlap with acoustic perception. This means that the low-frequency cutoff point determined by the audiogram lay somewhere between 300 and 1,000 Hz. The low frequencies may then be heard using the subject's preserved natural low-frequency hearing or using the HA part of the DUET speech processor. The DUET comprises a TEMPO+™ speech processor with precise Hilbert transform envelope detection and a two-channel HA in one unit. Only those electrodes inserted in the cochlea were activated, and electrodes were classified as intra- or extra-cochlear using impedance telemetry and reports of hearing sensation. The number of active electrodes was usually 8 for the standard and 11 for the medium electrode array in the PDCI group and 11 for the standard and FLEX arrays in the platinum HA user group. The upper frequency end was 8.5 kHz in all cases.

### Audiological and Speech Perception Testing

Pure tone testing was performed using a Siemens SD5 audiometer calibrated according to standards established by the American National Standards Institute. Testing was done in an IAC soundproof booth using Sennheiser HDA 200 headphones. A standard clinical procedure was used for determining the thresholds [33].

Subjects were tested using their natural bilateral acoustic hearing and their electrically stimulated hearing



**Fig. 1.** Preoperative and postoperative audiograms showing the mean and standard deviation for each frequency for two groups of patients. **a** Children who were platinum HA users preoperatively. **b** Children with PD.

via the CI in one ear or using a DUET speech processor, if they had been fitted with this. Audiological and speech reception tests under quiet conditions and in speech-shaped noise were performed preoperatively, then at implant fitting, and then at 3, 6, 12, 24, 36 and 48 months after the initial fitting of the device. Speech reception was tested using the Pruszewicz monosyllabic Polish word test (20 words per list, 20 lists) [34], with the lists of words being randomized between test conditions. The Pruszewicz monosyllable test is a consonant-nucleus-consonant test in Polish that is similar to the consonant-nucleus-consonant monosyllabic word test in English. Recorded words were presented in the sound field at 60 dB SPL in quiet and in competition with speech-shaped noise at a speech-to-noise ratio of +10 dB. The results of speech reception tests are the mean values obtained using 3 test lists.

## Results

### Hearing Preservation

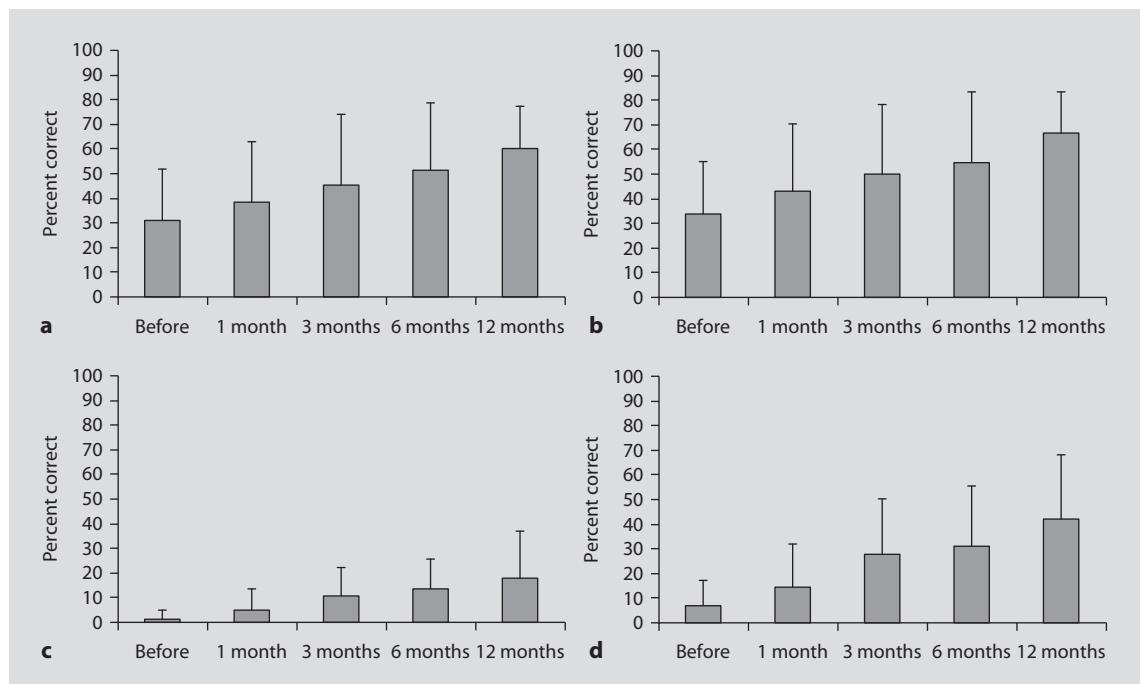
Hearing preservation immediately after the operation was achieved in all 25 children. However, 3 children could be considered as having non-functional partial preservation, because the low-frequency hearing could not be amplified with the HA component of the DUET in the implanted ear. Overall, hearing loss was not statistically

significant for all audiometric frequencies ( $p > 0.05$ ) either for platinum HA users or for children with PD. The average hearing thresholds, measured before surgery and 1–4 years afterwards, both for the PDCI and for the platinum HA user group, are shown in figure 1. The length of the electrode had no significant effect on the degree of change in the thresholds after surgery.

### Speech Perception

Four out of 15 PD children, and 5 out of 10 children from the platinum HA user group could not be assessed using the standard monosyllable test because it was too difficult for them. For this reason, these 9 subjects were excluded from the speech reception evaluation, leaving 16 subjects with at least 1 year experience of using the device.

The results of monosyllable testing under quiet conditions and under noisy conditions are presented in figure 2. The mean scores and their standard deviations are shown. The postimplant scores after 1 year of CI use exceeded the preimplant scores for all children. Children in both groups performed statistically significantly better with EAS over time under both quiet and



**Fig. 2.** Monosyllable scores over time: under quiet conditions in the platinum HA user group (**a**) and for children with PD (**b**); under noisy conditions in the platinum HA user group (**c**) and for children with PD (**d**). The mean and standard deviation for the electric acoustic conditions are shown.

noisy conditions compared with the preoperative acoustic HA condition. In addition, no significant differences were observed between the two groups under quiet conditions, although under noisy conditions there was a significant difference between the groups at 3, 6, and 12 months after implantation.

## Discussion

Hearing was preserved and found to be stable over the subsequent 1–4 years in all children implanted using the same round window surgical technique. There was no significant difference in the group comparing preoperative and postoperative thresholds either for children in the platinum HA user group or for children with PD. This was

in accordance with the findings of Willingham and Manolidis [28] who used ASSR thresholds to demonstrate that by employing a round window technique in children with residual hearing, there was no statistically significant change in auditory function in the implanted ear after implantation.

In the platinum group of HA users, the rate of functional preservation was 90% (9 out of 10). This result is better than the 71% of children (5 out of 7) with slightly poorer residual hearing previously achieved by the same author using cochleostomy [26].

In the group of 15 children with PD, the rate of functional preservation was 87% (13 out of 15). This is almost the same as the preservation rate of 88% achieved in the subgroup of the first 9 children with PD as previously reported [32]. It is also similar to the preservation rate of 90% achieved in

a group of 10 adult patients with PD [12]. The data support our conclusion that the results from our 'round window' hearing preservation technique are repeatable.

There were no significant group differences in the hearing threshold change between children from a platinum HA user group implanted using a full-length 30-mm electrode and children with PD implanted with a shallower 20-mm insertion.

It was decided to use the round window technique instead of cochleostomy because we believed that this would limit the loss of residual hearing. There are known potential problems with cochleostomy, such as (a) perilymph loss and acoustic trauma caused by drilling; (b) formation of new bone within the cochlea, caused by the presence of bone dust [35]; (c) risk of initiating osseous spiral lamina injury, and (d) damage due to infection, which may cause the formation of fibrous tissue [12, 36]. Some authors have used temporal bone studies to address these issues and have demonstrated the supremacy of the 'round window' approach over cochleostomy in preventing trauma to cochlear structures [37, 38].

Monosyllabic word recognition increased in the platinum group from 31 to 60% under quiet conditions and from 1 to 19% under noisy conditions over a period of 12 months.

In the PDCI group, the increase under quiet conditions was from 34 to 67% and under noisy conditions from 7 to 47%. These results achieved in the PD group are comparable to the results achieved previously in the subgroup of 9 children (from 30 to 69% under quiet conditions and from 5 to 62% under noisy conditions) [32]. This again confirmed that the results of PDCI are repeatable.

The increase in performance under quiet conditions was comparable in both groups, although the benefit under noisy conditions was significantly greater in the PD group than in the platinum HA user group. This finding reveals that in order to achieve any significant benefit under noisy conditions, good hearing at low frequencies

is needed. However, the low number of children tested in the platinum HA user group ( $n = 5$ ) means that this conclusion should be treated with caution and that further research is needed in this area.

Despite this, the encouraging improvement of speech discrimination under noisy conditions suggests that the benefit from EAS exceeds that usually seen in children who rely on only one CI system [39].

Those subjects who did not demonstrate functional hearing in the implanted ear after surgery were able to obtain a significant advantage by using a CI in one ear and relying on natural low-frequency hearing in the other. This observation is consistent with previous research that suggested that children with asymmetrical hearing loss with open-set sentence scores of above 30%, and up to 87% in the better ear, obtain a significant improvement in speech perception using a combination of ipsilateral electric stimulation via a CI, and contralateral acoustic stimulation, usually using an HA [22].

The significant rapid improvement in auditory capacity, as presented in figures 2, suggests that the gains in performance were due to CI intervention rather than to any progress that would have occurred in the course of rehabilitation with conventional HAs. Further research is needed to assess the role of EAS in the perception of the suprasegmental features of speech and music appreciation in children.

## Conclusion

The results presented herein indicate that by using the round window approach, it is possible to preserve good low-frequency hearing using a 20-mm insertion depth as well as preserve hearing using a longer 30-mm insertion.

There are two groups of children that may benefit from EAS, namely: (1) children who are platinum HA users preoperatively, who could be

considered as traditional CI candidates, and (2) children with a ski-slope type hearing loss, described herein as PD, whose preoperative hearing thresholds and auditory capacity exceed the normal selection criteria. Children from both groups show rapid improvement in their speech perception abilities after surgery, under quiet and noisy conditions. The parents of these children report a change in both listening behavior and in ease of listening. The same approach was applied in both groups in terms of the type of surgical procedure that was used to try to promote hearing preservation. As a consequence of this, the combination of electric and acoustic stimulation was possible

in both groups, and therefore we propose that the term 'PDCI' be widened to include children from a platinum HA user group preoperatively, and in broader terms, children with a functional degree of residual hearing. The provision of PDCI opens up the hearing world to these children.

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