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ORIGINAL ARTICLE

Partial deafness cochlear implantation provides benefit to a new population of individuals with hearing loss

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Abstract
Conclusion. Partial deafness cochlear implantation (PDCI) is a feasible means of treating individuals who have good low frequency hearing, but a severe to profound hearing loss in the mid to high frequencies. The individuals have benefit in noise and show significant benefit in a number of difficult listening conditions, when compared with their acoustic-only hearing prior to implantation. This benefit is maintained over time. *Objectives.* PDCI using the round window surgical technique is one means of treating individuals with a 'ski-slope' hearing loss, who gain minimal benefit from amplification with conventional hearing instruments. This paper aims to demonstrate the benefit that PDCI provides these individuals. *Patients and methods.* Ten subjects received a partial insertion of a standard MED-EL electrode, using the round window approach. Pure tone audiometry and monosyllable testing in quiet and noise were conducted preoperatively, at implant fitting and then at 1, 3, 6 and 12 months after initial device fitting. The APHAB questionnaire was completed by subjects preoperatively and then at 6 and 12 months after receiving their cochlear implant. *Results.* Hearing was preserved in 9 of 10 cases. One subject uses a hearing aid to amplify low frequency hearing, the remainder use natural low frequency hearing. Improvements in monosyllabic scores over time in both quiet and noise were significant, particularly within the first 3 months of PDCI use.

Keywords: *Partial deafness cochlear implantation, APHAB questionnaire, monosyllable testing*

Introduction

There is a large group of patients whose hearing impairment is characterized by normal or slightly elevated thresholds in the low frequency region, with nearly complete deafness in the higher frequencies, with an audiogram akin to a ski-slope hearing loss. Patients with good hearing only in the low frequencies are able to detect all the vowels, but probably few, if any, consonants. Low frequency perception can foster speech reading and speech production, and environmental sound awareness can contribute to the recognition of intended emotions.

However, such hearing still does not allow patients the ability to communicate efficiently in everyday life, particularly in noisy listening situations. Often these patients remain beyond the scope of effective treatment with hearing aids only, since amplification at frequencies above the region of substantial residual hearing provides little or no benefit for individuals with steeply sloping audiograms [1–5]. Moreover, this group of patients has not been considered as traditional cochlear implant candidates because it was feared that such intervention would damage the functioning part of the cochlea, causing complete hearing loss. Loss of residual hearing after cochlear implantation has been reported by several authors [6–8].

Electric acoustic stimulation (EAS) has been suggested as one technique to provide adequate amplification for such individuals [9]. Here the low frequencies are preserved during shallow cochlear implantation, and are amplified with an in-the-ear

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hearing aid. The mid to high frequencies are stimulated with a cochlear implant, and a behind-the-ear speech processor is fitted in the same ear. Results suggest hearing preservation following cochlear implantation to allow for sufficient amplification in the low frequencies [10–13]. Speech results confirm the significant benefit of EAS, demonstrating a strong synergistic effect of combining the hearing aid and cochlear implant in the same ear, most particularly noted in noise [12,13].

Based on the encouraging results obtained by combining electric and acoustic stimulation our centre decided to implant a partially deafened young woman, by conducting a partial insertion of the electrode into the cochlea [14]. After 3 months of experience with the implant, scores for recognition of monosyllables in quiet increased from 23% preoperatively to 90% postoperatively; and scores for recognition in noise increased from 0% to 65%. These results demonstrated a substantial improvement in speech discrimination and communication skills when electric stimulation on one side was combined with natural acoustic stimulation on both sides. This finding created new possibilities for partially deafened patients. However, to implement this new method of partial deafness treatment, further research is needed to prove the possibility of low frequencies hearing preservation and to demonstrate the significant speech perception benefit that such implantation may provide.

This study aimed to demonstrate the objective and subjective speech perception benefits from partial deafness cochlear implantation (PDCI) when partially inserting a MED-EL COMBI 40+ electrode using the round window surgical technique.

Patients and methods

Subjects

Ten patients with partial deafness were implanted using the round window technique. Figure 1 shows the mean preoperative audiogram for these subjects. Seven females and three males are reported on here. The mean age at implantation was 39.1 years (range 26–64 years). Six subjects have unknown aetiology, two had meningitis in childhood, one has familial history and one subject has an ototoxic hearing loss. Any subjects with a progressive hearing loss are excluded from PDCI. Progressive hearing loss is defined as a 10 dB shift at two consecutive frequencies or a 15 dB shift at one frequency over a period of 1 year. Duration of deafness cannot be calculated, as most subjects reported that although they had later diagnosis, they felt they had the hearing loss for a long time, all patients who have unknown aetiology believe they had their hearing loss from birth. All subjects were in tertiary education or had a tertiary-level degree. Subjects were aware of the benefits and risks posed by PDCI. Table I details patient demographics.

Surgical technique and device used

All subjects were implanted with a MED-EL COMBI 40+ standard electrode array which was partially inserted. Insertion depth was based on the subject's preoperative audiogram. Surgery was performed using the round window technique. All subjects were implanted in the worse ear in cases where hearing losses were not completely symmetrical, and in the perceived worse ear in cases where the hearing loss was bilaterally symmetrical.

CI programming

As there is only partial insertion of the electrode, careful consideration of programming the device is required. Only those electrodes inserted in the cochlea are activated and this is determined based on telemetry and reported hearing sensation. Frequency of electrodes is determined by the audiogram. The aim is to programme the cochlear implant without any overlap with acoustic perception, so as to not interfere with this perception. This is usually between 500 Hz and 1000 Hz. Electrode frequency modification can be adjusted on the cochlear implant fitting software.

Audiological testing

Pure-tone testing was performed using a Siemens SD5 audiometer calibrated according to standards established by the American National Standards Institute (ANSI). The maximum output of the audiometer was 130 dB HL, and a standard clinical procedure was used for threshold determination [15]. Testing was performed in an IAC soundproofed booth under Sennheiser HDA 200 headphones.

Speech perception testing

Subjects were tested using their natural bilateral acoustic hearing and electrically stimulated hearing via the cochlear implant in one ear. Tests of speech comprehension were performed using the Pruszewicz monosyllabic Polish word test (20 words per list, 20 lists). Lists of each test were randomized

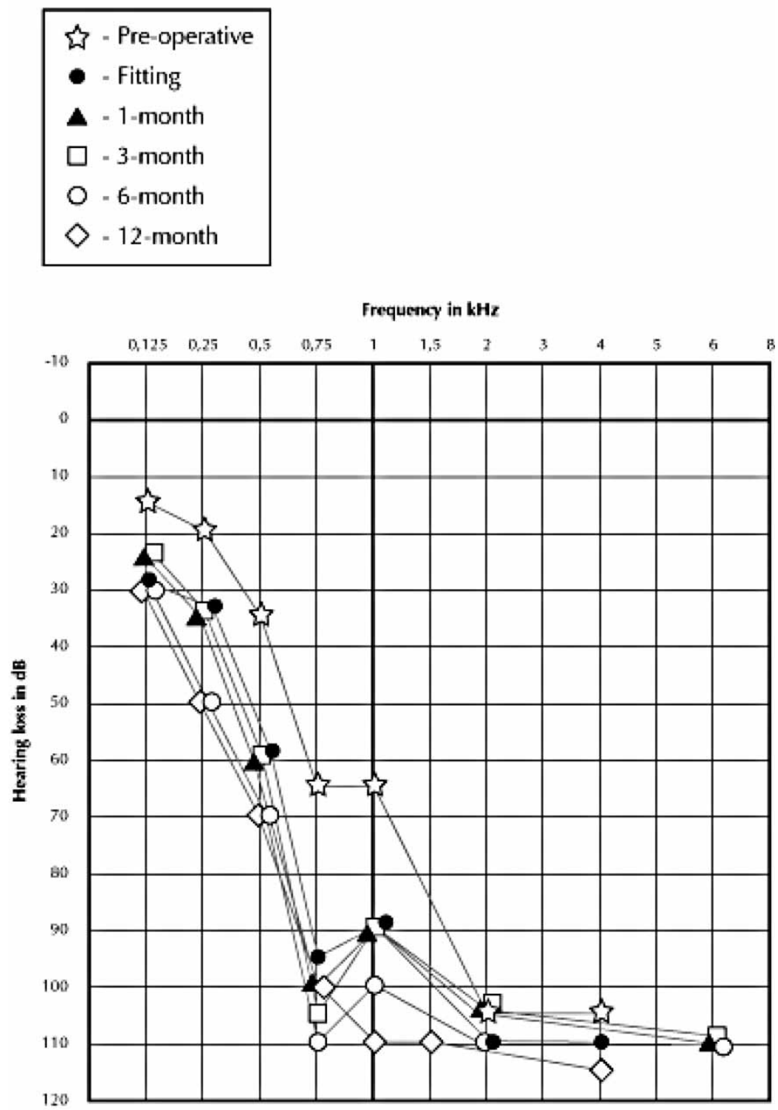

Figure 1. Mean audiograms for PDCI subjects recorded preoperatively, at cochlear implant fitting, then at 1, 3, 6 and 12 months after initial fitting. This audiogram excludes the subject who lost all hearing after surgery.

among test conditions. Results given are the mean values of three test lists. Monosyllable tests were also conducted in noise at a SNR of 10 dB. Sentences were tested using the Polish adaptation of the HSM sentence test. Sentences were tested in quiet and at a SNR of 10 dB. Speech tests were conducted preoperatively and at 1, 3, 6 and 12 months after cochlear implantation.

Table I. Description of each subject including age at implantation, age at diagnosis, aetiology and subject's educational level.

Subject	Age at CI	Age at diagnosis	Aetiology	Educational level
KT	26	6	Unknown	Student
GD	50	18	Familial	Lawyer
ZS	46	5	Unknown	Office worker
KJ	64	31	Ototoxic	University lecturer
SB	48	Teens	Unknown	Priest
MJ	26	15	Unknown	Student
MP	29	4	Meningitis	Engineer
BS	28	8 months	Meningitis	Student
MM	32	28	Unknown	Chemist
LT	42	Childhood	Unknown	Nurse

Subjective benefit

Each subject was assessed using the APHAB questionnaire to determine benefit from PDCI. The APHAB [16] measures benefit from cochlear implantation in comparison to the preoperative condition, and is sensitive to changes over time. The APHAB has four subscales, assessing hearing under a number of difficult listening situations. 'Ease of communication' (EC) assesses speech understanding under relatively favourable conditions, 'reverberation' (RV) assesses communication in reverberant conditions, 'background noise' (BN) assesses communication in noisy settings, and 'aversiveness' (AV) assesses the unpleasantness of environmental sounds. The APHAB was completed by each subject preoperatively, then at 6 and 12 months postoperatively.

Statistical analysis

In addition to graphical analyses and the employment of descriptive measures such as averages or medians, the statistical analysis of this study included inferential statistics for speech test data and the APHAB results. In order to study the development of scores over time for speech data, a repeated measures ANOVA was used. These analyses were made for monosyllables in quiet and in noise. Using ANOVA we could not only analyse the overall impact of time on results but also the pairwise results, i.e. analyses include a direct comparison between single points in time. To emphasize the pairwise results from ANOVA for the implanted ear we used Wilcoxon signed ranks test and compared speech data for single points in time. ANOVA with repeated measurements was used to analyse APHAB results. However, due to the small sample size these results can only be used to show general tendencies. Descriptive measures and graphs were used to analyse the data from APHAB. Additionally, the Wilcoxon signed ranks test was used to assess development over time when comparing the results between 6 and 12 months on the APHAB. All statistical significance has been calculated at 10%.

Results

Surgical outcomes and hearing preservation

No complications during surgery were noted. All except one subject had preservation of hearing after surgery; all other subjects had preserved or partially preserved hearing. Figure 1 shows the average audiogram for the nine subjects with hearing preservation for each test interval. Hearing decreased significantly from the preoperative to first fitting interval for 125 Hz ($p = 0.031$), 250 Hz ($p = 0.016$), 500 Hz ($p = 0.016$) and 1000 Hz ($p = 0.094$). No other differences were noted when comparing the test intervals and frequencies, except at 250 Hz between 6 and 12 months ($p = 0.063$). Eight of these subjects use their natural acoustic low frequency together with their cochlear implant for everyday listening. One subject uses a hearing aid to amplify the low frequencies and a cochlear implant to amplify the high frequencies, with both devices fitted in the same ear.

Speech perception testing

Results of monosyllable testing in quiet are shown in Figure 2. Results over time are significant ($p = 0.000$ with Greenhouse-Geisser correction). The pairwise comparisons show that the effects are significant between preoperative and 1 month ($p = 0.091$), preoperative and 3 months ($p = 0.001$), preoperative and 6 months ($p = 0.000$), and preoperative and 12 months ($p = 0.000$). There is also a significant improvement between 1 and 3 months ($p = 0.016$), and 3 to 6 months ($p = 0.031$); although there is improvement between 6 and 12 months, this is not significant.

Figure 3 shows the scores for monosyllable testing in noise. There is a significant increase in scores over time from preoperative to 12 months ($p = 0.000$). The pairwise results are significant for preoperative to 3 months ($p = 0.007$), preoperative to 6 months ($p = 0.002$), and preoperative to 12 months ($p = 0.004$). Improvement between each test interval was also assessed. The 1 month to 3 month improvement was significant ($p = 0.010$), as well as the 3 to 6 month improvement ($p = 0.047$). As for the monosyllables in quiet, the improvement was not statistically significant. Thus, there is a significant increase during the first periods. There seems to be a

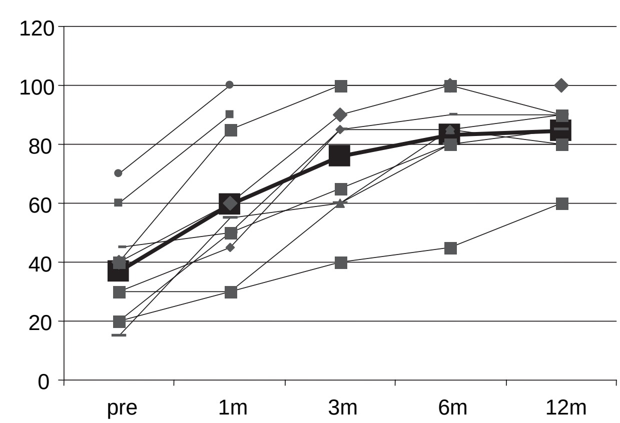

Figure 2. Monosyllable scores in quiet for each individual PDCI subject over time. The bold bar with square markers shows the mean monosyllable score over time.

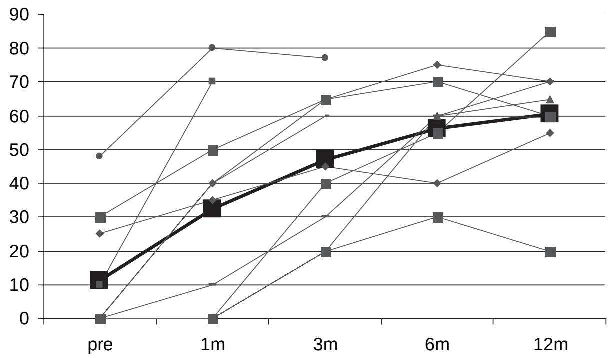

Figure 3. Monosyllable scores in noise for each individual PDCI subject over time. The bold bar with square markers shows the mean monosyllable score over time.

plateau effect after 3 months, as there are only smaller increases in scores.

As can be expected, performance in quiet is significantly better than in noise at all test intervals: preoperative ($p = 0.002$), 1 month ($p = 0.002$), 3 months ($p = 0.004$), 6 months ($p = 0.008$) and 12 months ($p = 0.016$).

APHAB results

The APHAB results are reported as a global score, and the subscales: ease of communication, reverberation, background noise and aversiveness. Scores are calculated as a difference from one test interval to another (Figure 4). Global APHAB scores show a significant decrease over time ($p = 0.026$), which means an improvement in benefit. Pairwise results are significant between the preoperative and 6 months period ($p = 0.085$) and the preoperative and 12 month period ($p = 0.087$), but not between the 6 and 12 month period. The 'ease of communication' subscale showed a significant decrease in scores over time ($p = 0.012$), with the significant effect being from the preoperative to 12-month interval ($p = 0.071$). The significant decrease over time for the 'reverberation' subscale ($p = 0.012$) was mostly influenced by the significant change in benefit for the preoperative to 6-month test interval ($p = 0.086$). The overall decrease in scores over time was significant ($p = 0.070$) for the 'background noise' subscale, but no significance between intervals. There was no significant difference in scores for the 'aversiveness' subscale. Figure 4 shows the decrease in scores (thus benefit gained) for the global score, as well as for each subscale.

Discussion

The results shown indicate that with careful delicate surgery and a limited electrode insertion, hearing can be preserved in the majority of patients with a ski-slope hearing loss, who gain limited benefit from a hearing aid. This preservation allows subjects access to low frequency hearing, which can benefit their speech perception outcomes.

The question as to how limited the insertion should be can be raised. Our centre believes in representing the tonotopicity of the cochlea as closely as possible, thus having a limited insertion depth of approximately 18–20 mm to allow the patient access to the high and mid frequency regions of the cochlea. Results using a 6 mm electrode and a 10 mm electrode showed better scores with the 10 mm electrode, due to a reduction in the mismatch between speech frequencies assigned to the implant and the normal tonotopic map of the cochlea [11]. Our centre wished to reduce this mismatch even further by having a deeper insertion of the electrode based on the subject's audiogram. This decision was

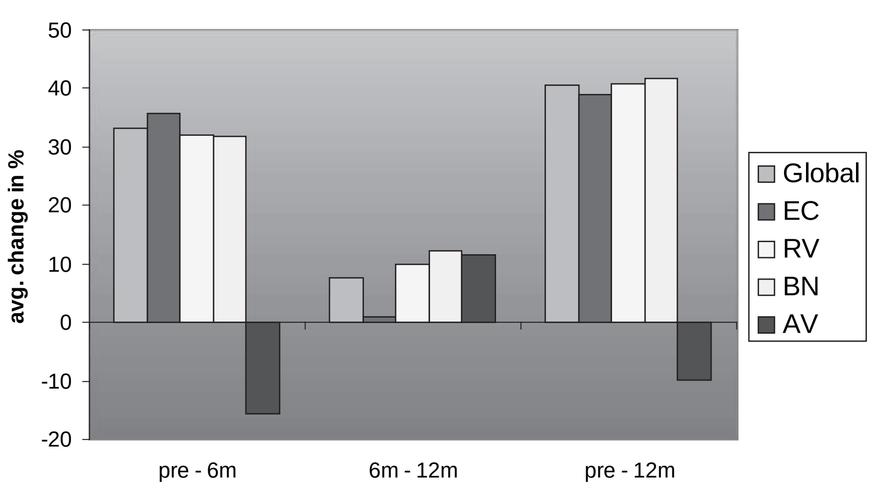

Figure 4. APHAB scores of the PDCI subjects comparing preoperative to 6 month differences, 6 to 12 month differences, and the accumulation of these, being preoperative to 12 months differences. Global, total score of each subscale; EC, ease of communication; RV, reverberation; BN, background noise; AV, aversiveness.

further reinforced by depth of insertion simulations conducted with normal hearing individuals [17]. This study demonstrated that an insertion depth of 17–19 mm provided the best level of speech understanding; with a 19 mm insertion showing 40% better speech perception than an 11 mm insertion. In cases where a hearing loss was simulated, only deeper insertions of 19 mm and 17 mm allowed for better speech understanding when compared to acoustic hearing only.

Similar results are confirmed in real world cases where hearing was preserved to some degree in 12 of 14 cases [10] and showed mean monosyllables of 58% at 6 months after surgery. This is somewhat lower than the scores reported in our case (83%). However, if the differences in preoperative scores (9% to our 37%) are compared, it becomes clear that two different population groups have been implanted. In our instance, the subjects have significantly better speech scores to begin with, which reflects the better low frequency hearing. Our subjects (except for one) do not need to wear hearing aids to amplify the low frequency region, and thus are able to use their natural low frequency hearing together with electrical amplification via their cochlear implant to obtain excellent speech perception scores. This is even seen in the more difficult listening condition of background noise, where a mean score of 56% is seen for monosyllables at 6 months. This synergistic effect of combining electric and acoustic hearing has been reported elsewhere [13].

It is important to consider the difficult listening conditions a subject may face in everyday situations. One way of measuring this is through questionnaires. The APHAB questionnaire measures changes in benefit over time. In this instance, we can see a significant change in perceived difficulties in hearing under various listening conditions. A global benefit of 33% between the preoperative interval and 6 months is recorded, although somewhat less, an improvement of 7% was reported between 6 and 12 months, and we may yet still see a change further over time. There was one condition where listening worsened: aversiveness (AV), which measures unpleasantness of environmental sounds. This worsened by 15.7% 6 months after implantation, after 12 months this improved slightly by 11.5%, but overall, after 12 months, there was still a negative benefit of 9.9%. This may suggest that the sound takes some time to become accustomed to, or when reviewing the answers, we may see the influence of fitting here; where the programme of the cochlear implant has been boosted to give a lot of high frequency emphasis. Although none of the subjects complained about this aspect, we see that it has an adverse effect in one listening situation, and should be considered. Significant improvements in listening conditions such as background noise, hearing in reverberant environments and improvement in ease of communication mirror the speech testing outcomes, and suggest the significant benefit that PDCI provides these individuals over and above their hearing experiences with acoustic amplification only.

Finally, one would ask the question: what is the risk versus the benefit? The risk, in this case, is losing a significant amount or all of the available low frequency hearing. In our group, only one subject lost hearing completely, one has lost hearing and requires amplification with a hearing aid, and the remainder have preserved hearing within a useable range, without acoustic amplification. The questions might be whether one should not implant at all and use acoustic stimulation or not be concerned about preserving the low frequency hearing for acoustic stimulation, and provide the subject with a full insertion and cochlear implant stimulation only.

Our results demonstrate the significant benefit over standard implantation, especially in noise, an often reported difficult listening condition for cochlear implant users. Our data also show that even the subject with lost hearing shows significant benefit from her implant. This point concurs with the outcomes of simulation testing [17], which showed that relatively deep insertion allowed better speech understanding than the acoustic-only condition and this justified the risk.

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