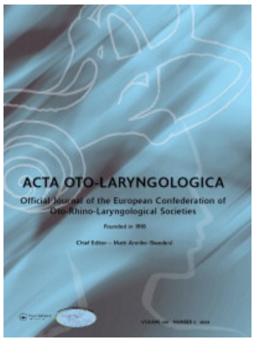

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RESEARCH ARTICLE

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Cochlear implantation and partial deafness - A retrospective review on processor programming

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ABSTRACT

Background: To decide what programming parameters to use for cochlear implants (CIs) in partial deaf patients can be challenging.
Objective: The processor programming form, categorised as electrical complement (EC), electro-acoustic-stimulation (EAS) or electric stimulation (ES), and difficulties switching programming form were investigated.
Methods: A retrospective investigation of medical records and audiograms was conducted in adult patients intended for EC and EAS.
Results: Eighty-four ears (80 patients) were included. Twenty ears were initially fitted with EC, 32 with EAS, 30 with ES and 2 with both EC and EAS. Sixty-four ears met the criteria to use EC or EAS at initial fitting, however only 54 ears were fitted with EC or EAS initially. Twenty-eight patients altered between at least two programming forms and six of those experienced difficulties to adapt to a new form when their low-frequency hearing deteriorated. Twenty-five percent of patients initially fitted with EC or EAS switched programming form within two years.
Discussion: Further studies on how to choose the most beneficial sound processor programming parameters for EC and EAS, and when to change between programming forms, are warranted as well as clear guidance on choosing the right candidates for EC and EAS.

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Partial deafness; electro-acoustic stimulation; long-time follow-up; programming

Introduction

Since 2002 patients with partial deafness have been treated with electro-acoustic stimulation (EAS) [1]. Hybrid hearing requires preserved low-frequency hearing and studies have shown hearing preservation after cochlear implantation (CI), but that the residual hearing declines over time for most patients [2–5]. Managing mapping and programming of the sound processors for patients with partial deafness has acquired considerably less attention in published studies than reports on preserved hearing [6]. Most studies give little information on how to optimise programming of the processor for cochlear implantation partial deafness treatment (CI-PDT). Processors for these patients can be programmed in numerous ways, with or without hearing aid amplification and with different crossover frequencies between the electric and acoustic stimulation. Furthermore, different electrical stimulation strategies may be employed (i.e. HDCIS, FSP or FS4). We therefore sought to explore parameters for sound processor programming for this group of patients.

CI-PDT results in three different programming forms: natural hearing for low to mid frequencies and CI-hearing for the mid to high frequencies (electrical complement, EC), hearing aid amplification for the low to mid frequencies and CI-hearing for the mid to high frequencies (electro acoustic stimulation, EAS) or CI-hearing for all frequencies (electric stimulation, ES) [7]. Earlier studies found that only 50-70% of patients with preserved hearing used EC or EAS strategies for various reasons [8,9]. The reason may be individually based but also a lack of consensus regarding fitting procedure and definition criteria of usable preserved hearing and patient selection. In a study of EAS patients, Payne et al. (2023) concluded that hearing outcome varies widely, and the optimal fitting procedure and frequency assignments for the two hearing devices in EAS (the electrical and the acoustical part) remains unclear [10]. Mamelle and colleagues [11] found in their study of 81 implanted ears intended for EAS that, although hearing preservation was observed in 93% of the cases, only half of them initially benefitted from EAS.

When CI-PDT was initiated in our clinic in 2008, candidacy criteria for EC and EAS were unaided pure-tone threshold ≤65 dB HL at frequencies ≤500 Hz and >80 dB HL at frequencies ≥2000 Hz in the ear intended for surgery. The hearing should be nearly symmetrical and aided monosyllabic word scores in free field should be < 60% in each ear. Since then, there has been a shift in candidacy criteria at

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our clinic as well as from the implant manufacturers. Currently we require low-frequency hearing (low-frequencies defined as frequencies below 750 Hz) to be < 50 dB HL, and CI-PDT is not offered to patients with normal hearing at 1000 Hz. The shortest electrodes are used if the patient is expected to use EC. EC is offered when the low-frequency hearing is near normal with no signs of rapid progressive hearing loss.

A challenge programming the processors for CI-PDT is to avoid electric-acoustic overlap and optimise the boundary (the crossover frequency) between the two simulation modes (electric and acoustic). Figure 1 shows a schematic illustration of the implanted electrode in the cochlea and how the electrode contacts can be located and programmed. By Figure 1 an attempt is made to explain the complexity in programming the processor for EC or EAS. In case A all electrode contacts are used, and they overlap the acoustic stimulation. In this example, a long electrode array has been used, or the patient has an unusually small cochlea. The acoustic stimulation can be with or without hearing aid amplification. In example B, electrodes 1 to 3 are switched off in the software and electrodes 4 to 12 are used for electrical stimulation. This changes the frequency allocation table for the electrode contacts on the implant which can be a problem later if electrodes 1 to 3 are switched back on, since the frequency allocation table then changes again. In example C all electrode contacts are used for electrical stimulation, but electrode contact 1 to 3 are set to 0 in order not to change the frequency allocation table for the electrode contacts. In example D a short electrode has been used, or the patient has an unusually big cochlea, and there is a gap between the acoustic and the electrical stimulation.

To overcome the problem of electric-acoustic overlap, CT-imaging can provide information about optimal electrode length and monitor individual place/frequency maps after implantation. This can be accomplished by using the OTOPLAN software developed by CAScination (Bern, Switzerland) in cooperation with MED-EL (Innsbruck, Austria). In our clinic, CT-imaging is used to decide electrode length but not for the post-surgery programming. A post-surgery unaided audiogram is used to decide where to put the crossover frequency for the electric and acoustic stimulation and when needed to program the acoustic part of the processor. According to the programming guidelines from MED-EL (Innsbruck, Austria) the crossover frequency can be found where the hearing loss crosses the 65 dB HL line on the audiogram. Previously, it was recommended to set the crossover frequency as the minimum frequency for the electrical stimulation and the processor was programmed with all electrodes active. Nowadays the electrodes not used for electrical stimulation is set to 0 stimulation level, and the minimum frequency for the electrical stimulation is left

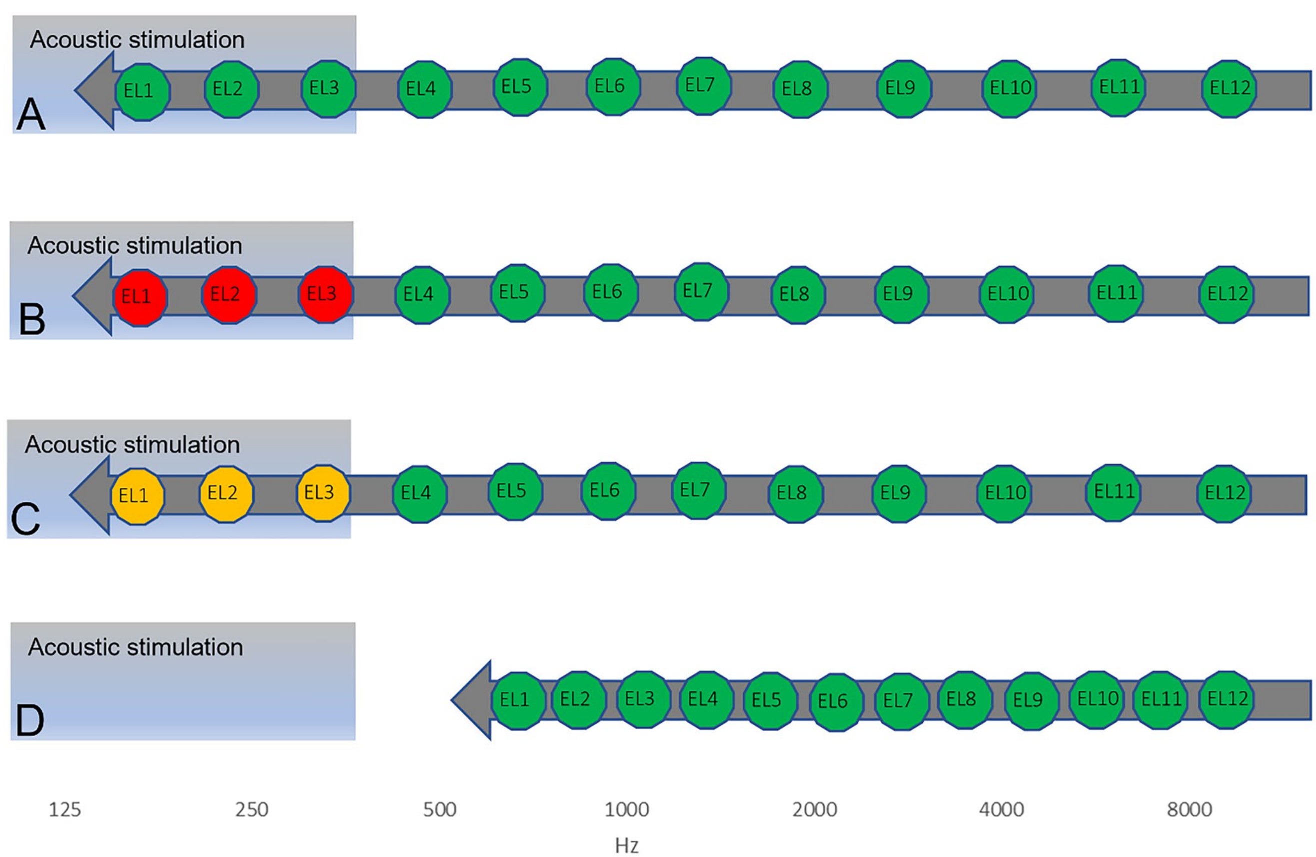

Figure 1. Schematic illustration of implanted electrode in the cochlea. Shaded area represents residual hearing aimed for acoustic stimulation. Green electrodes are active, while yellow contacts are active electrodes set to 0 stimulation level. Red electrode contacts are deactivated. A) All electrode contacts are active and overlapping acoustic stimulation. B) Electrode contact 1 to 3 are deactivated while electrode contact 4 to 12 are active. C) All electrode contacts are used for electrical stimulation, but electrode contact 1 to 3 are set to 0. D) A short electrode array is used, or the cochlea is unusually long. There is a gap between the acoustic and electrical stimulation. EL = electrode.

unchanged, to avoid change of the frequency allocation table for the individual electrodes if a reprogramming is needed later. The processors at our clinic were programmed as recommended by MED-EL (Innsbruck, Austria) at the time the patient got implanted. However, the patients sometimes choose another programming than recommended for reasons like unwillingness to wear an earmold or that they did not like the sound from the acoustic part in the processor. The patients at our clinic have to a large extent been involved in the decision on what programming to use in their processor. We have noticed that switching to a new programming form when residual hearing deteriorates in some cases led to several extra appointments at the clinic and even that some patients had difficulties to adapt to a new form. We wanted to explore the switching process in CI-PDT patients.

In the present study we scrutinised all patients intended for EC or EAS. The programming form they were first programmed with (EC, EAS or ES), duration each patient remained in each programming form and if they experienced difficulties if altered between forms were investigated. Differences between pre- and post-lingual hearing impairment, influence of age at implantation and pre-surgery low-frequency thresholds (LFTs) were also analysed.

The aims of this study were to investigate how many patients initially fitted with EC or EAS that switched processor programming form during the first two years post-surgery, and if the switch between forms involved any difficulties. An additional aim was to address the complexity in choosing the most beneficial processor programming parameters for these patients.

Materials and methods

This is a retrospective investigation of adult patients who were intended for EC or EAS. All adult patients, aged ≥ 18 years at the time of data collection, who were implanted two years ago or earlier with a MED-EL (Innsbruck, Austria) implant with the electrodes Flex 20, Flex 24 or Flex 28 and pre-surgery were intended for EC or EAS stimulation, were extracted from our database. Parts of this patient group have earlier been included in studies regarding hearing preservation and EAS at our clinic [2,4,12].

The medical records were searched for the following information: birth date, implantation date, electrode type, if the hearing impairment was pre- or post-lingual, processor at first fitting, dates for switching between the three defined forms of CI-PDT and if they experienced any difficulties switching form. Pre-lingual hearing impairment was defined as hearing loss from birth or in early childhood, before acquiring language. It was concluded from the medical records if the patient had reported subjective difficulties adapting to a new programming form. The crossover frequency for EC or EAS for the first fitting was searched for when appliable. If the crossover frequency was ≤ 100 Hz the fitting was categorised as ES. Also, each subject's hearing on the contralateral ear was extracted (no hearing amplification, hearing aid, EC, EAS or ES/CI). Audiograms were search for the low-frequency hearing threshold (125, 250 and 500 Hz) on the implanted ear both prior to implantation and after implantation. If the LFT pure tone average (PTA) after implantation was >65dB HL the hearing was categorised as "No post implantation hearing to amplify".

For the statistic calculations IBM SPSS Statistics (version 28.0.1.0) was used. A Kruskal Wallis test was used to analyse the non-parametric data and Bonferroni correction was used to adjust for repeated measures when applicable ($\alpha = 0.05$). Correlation between pre-surgery hearing (LFT PTA) and age at surgery was calculated using Spearman's rank correlation coefficient (r_s).

Results

Eighty-four ears (80 patients) intended for EC or EAS were included (Figure 2). Thirty ears (35.7%) were directly fitted with ES and never changed form. The reason for initial ES fitting was pre-surgery LFT PTA ≥ 60 dB HL ($N=10$), no post-surgery hearing ($N=9$), poor pre-surgery speech perception ($N=5$), patient's prefer ES despite well preserved low-frequency threshold ($N=2$), unwillingness to hearing mould ($N=1$), no subjective hearing improvement by either forms ($N=1$), pre-surgery

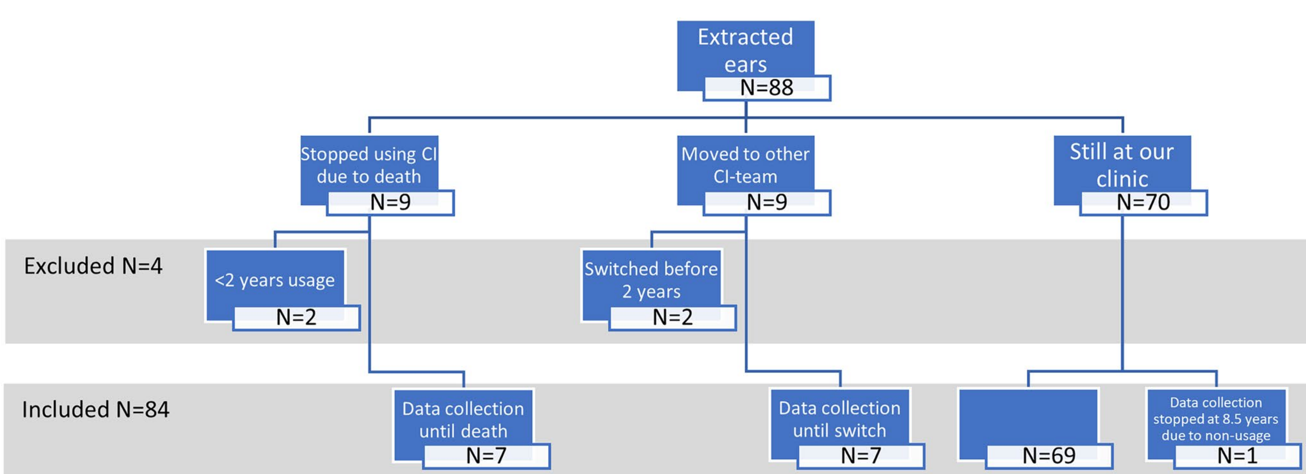

Figure 2. Enrolment of patients in the present investigation. N = number of ears.

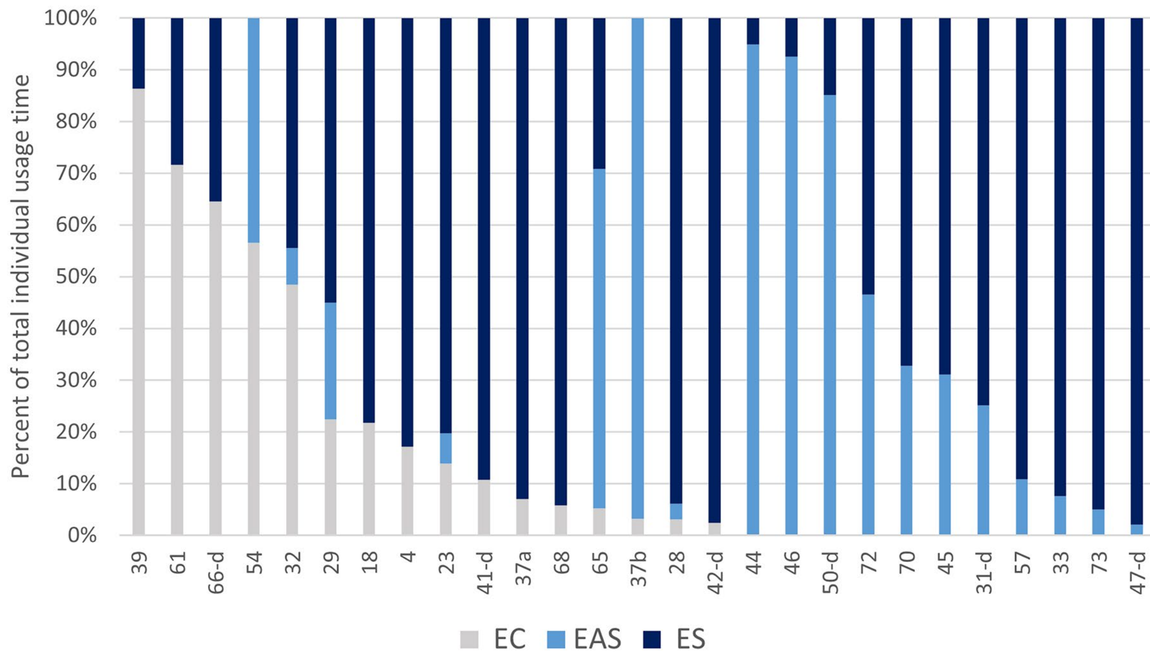

Figure 3. Individual use of different programming forms over time (for patients that switched programming forms at least once). EC – electrical complement, EAS – electro-acoustic stimulation, ES – electric stimulation. Y-axis showing the percentage of total usage time in each form. "-d" after patient no. indicates the patients experiencing difficulties switching between forms.

flat hearing loss ($N = 1$) and bilateral implantation where patient wanted same programming on both ears ($N = 1$).

Twenty ears (23.8%) were initially fitted in the EC form with crossover frequency between 150 and 900 Hz, with a mean frequency of 417 Hz. Fifteen of the 20 ears (75%) first fitted with EC used EC for ≥ 2 years before switching form or are still using EC. Thirty-two ears (38.1%) were first fitted in EAS form with crossover frequency between 188 and 900 Hz, with a mean frequency of 446 Hz. Twenty-four of the 32 patients (75%) first fitted with EAS used it for ≥ 2 years before switching form or are still using EAS. Two ears (2.4%) were fitted with both EC and EAS programs and those patients used both forms equally (crossover frequency 900 and 450 Hz respectively). In summary, 54 ears (64.3%) were first fitted with EC or EAS. The Supplementary Information shows details of each patient.

In 28 of the 54 ears (51.9%) fitted with EC or EAS, there was a switch between at least two forms, six of those used all three forms and one of them switched between the three forms depending on situation but mainly used EC. Figure 3 shows the twenty-seven ears (the one switching depending on situation excluded) that switched between at least two forms and their percentage of usage time in each form. Most patients switched forms in the order EC to EAS to ES or EAS to ES. Fifteen patients switched form during the first two years after first fitting. Figure 4 shows the time they spent in each form (the patient switching form depending on situation excluded since main usage form is EC).

Twenty-two out of 28 patients switched unproblematic between programming forms. Six patients (21.4%) experienced difficulties in switching between programming forms (pat no. 31, 41, 42, 47, 50 and 66). Each of these patient's experience is presented in Table 1. No statistically significant differences were found between age and pre-surgery LFT PTA compared to the rest of the patients that switched programming form ($p > 0.05$).

Concerning the 84 ears (80 patients) intended for EC or EAS, analysation of the different electrode lengths and pre-surgery LTF PTA showed no statistically significant difference between the electrode lengths ($p > 0.05$). Pairwise comparisons of electrode length and surgery age, showed significant differences between all electrode lengths ($p < 0.01$), the shorter electrodes had been given to younger patients (Figure 5). Bonferroni correction has been used to correct for repeated measures.

Age at surgery and electrode length showed no statistically significant difference between the programming forms at first fitting ($p > 0.05$). Pre-surgery LFT PTA and programming form at first fitting showed a statistically significant difference (EC versus ES, $p < 0.001$) and (EAS versus ES, $p = 0.03$). ES was more often used in patients with poor pre-surgery LFT PTA than EC and EAS (Figure 6). There was no correlation between age at surgery and LFT PTA ($r_s = 0.48$, $p = 0.18$).

Fifty-eight ears in this study were from patients with post-lingual deafness and 26 with pre-lingual deafness. There was no statistically significant difference between the two groups regarding the time spent with each programming form or difficulty switching forms ($p > 0.05$).

Discussion

Similar to Mamelle [11] we found that electrode length did not influence the use of different programming forms. Most patients in the present study did not change programming form (67%) which may in some cases hinder the use of an even better programming. Sixty-four patients could have

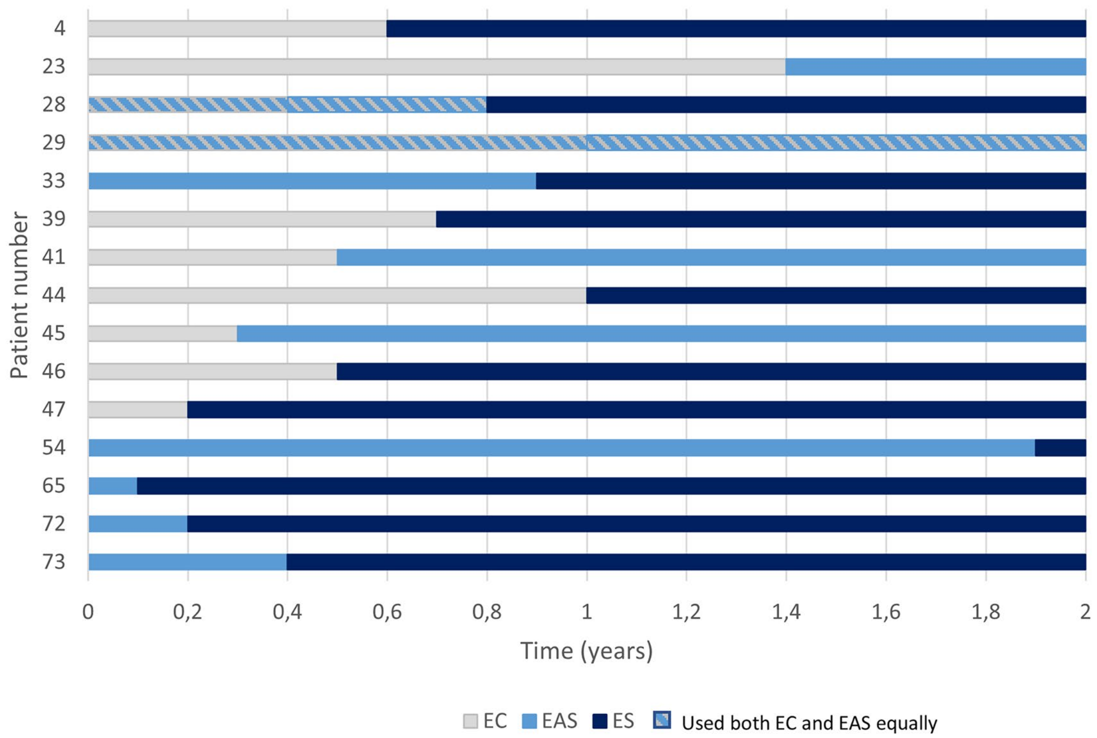

Figure 4. Time used with different programming forms during the first two years after fitting. EC – electric complement, EAS – electro acoustic stimulation, ES – electric stimulation.

Table 1. Patient experiences at switching programming forms.

Patient no.	
31	Difficulties to get used to the sound from first fitting. Did try both EC and EAS at first, choose EAS during the initial period. When getting a new hearing aid on the contralateral ear the EAS worked better. After 3 years changed to ES and had trouble getting used to the new sound. Patient more satisfied with implant sound after retirement.
41	Had a hard time switching from EAS to ES when the LFT deteriorated. Perceived poorer sound quality from ES. Pre-lingual hearing impairment. The eyesight also deteriorated at the same time as the LFT and patient after that had a hard time lip reading. Got a new hearing aid on the contralateral ear and could not be used to wear the two aids together, could not simultaneously benefit from ES and the new hearing aid.
42	Had a hard time from the beginning to get used to high frequency sounds and struggled for years to get used to EC. When LFT deteriorated it took a long time to get used to ES, still does not think the sound is as good as it was with EC. Comorbidity with depression and mobility problems. High demands at work. Post-lingual hearing impaired but unclear for how long.
47	Started with EC, tested EAS at 2 months but did not like the sound. From 2 months used ES. Finds the change from EC to ES troublesome. Have had a tuff time at work during that period with too much workload and had trouble finding vocational assistive devices that functioned at work.
50	Started with ES but had trouble getting used to it. Fitted with EAS after 1 month. After 3 months the hearing in the implanted ear started to deteriorate, after 6 months the hearing on the contralateral ear started to deteriorate. Tried ES after 3 years but the patient could not tolerate the change. Got implanted with a CI in the contralateral ear and during the first period with that device the programming is changed to ES without difficulties. Patient has a history of mental health problems.
66	Did not use hearing aids pre-surgery, could not get used to the sound. Tried both EC and EAS during the first period with the implant. Choose to use EAS after 3 months. At the same time started to use hearing aid in the contralateral ear. The hearing in both ears start to deteriorate after 3 years, after 4 years changes to ES. Struggled for a while to get used to ES.

been fitted with EC or EAS since they had preserved LFTs post-surgery, but only 84.3% were fitted accordingly. The number is higher than data presented in other studies [8,9], even though comparisons are difficult due to the lack of universal guidance criteria for using different stimulation modes [8,10]. One reason for patients choosing ES despite well-preserved LTFs may be the technological need for adapting to other devices such as TV and mobile phones. If the patient's processor is programmed for EC, the connected device cannot be used for the unaided low-frequencies since there is nothing to connect to. This leads to a difficult situation for the patient and may represent a reason to choose ES or EAS despite preserved LFTs. Our experience is that many patients find it hard to understand the concept of hybrid hearing with different outcomes of hearing preservation surgery leading to several programme combinations. This is a challenge when encouraging the patient to compare two different programme forms. It's not easy to find a common language while discussing EC and EAS with a patient.

Six out of 28 patients (21.4%) who switched between different forms experienced difficulties to cope with the new programming form. Factors like vision impairment, depression, occupational fatigue, and degraded hearing on the contralateral ear seemed to be contributing factors. In addition, all but one of these patients were still at work and the

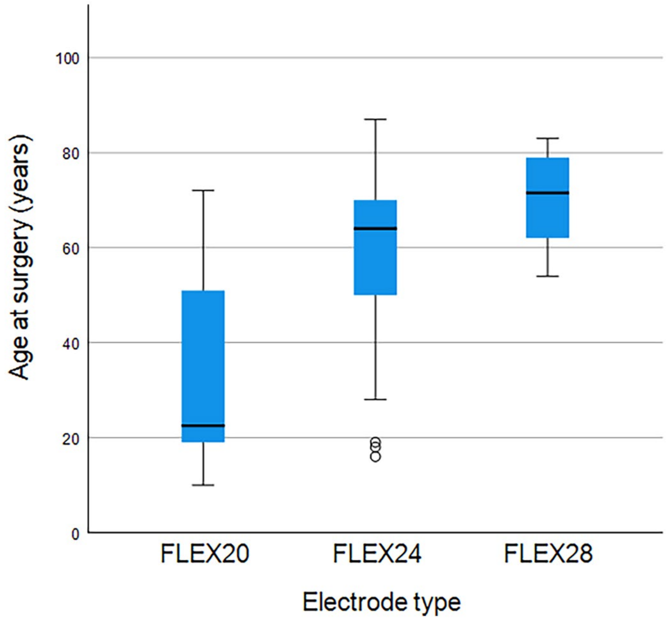

Figure 5. Type of electrode and surgery age.

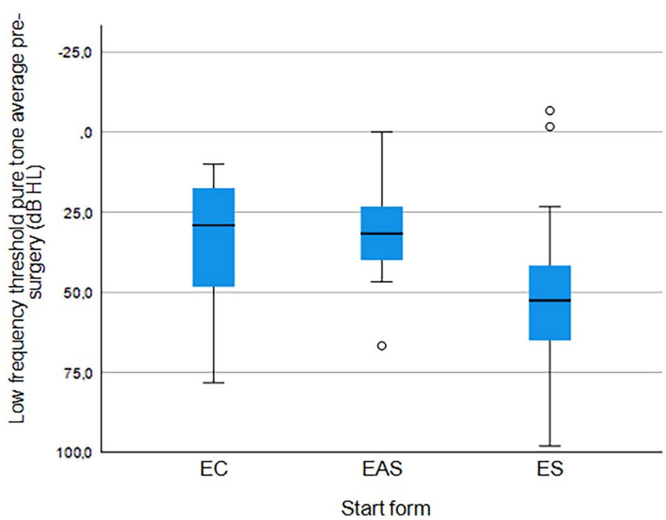

Figure 6. Pre-surgery low-frequency threshold pure tone average (LFT PTA) and initial programming form. EC – electrical compliment, EAS – electro acoustic stimulation, ES – electric stimulation.

demands on the implant hearing outcome were high both from their employers and the patients themselves. The problems with switching forms affected a smaller number of patients than we had expected. Nevertheless, 25% of patients initially fitted with EC or EAS must switch form less than two years post-fitting. Each switch consumes a considerable amount of time, both for the patient, often with sick leave, and the clinic. More appropriate inclusion criteria for EC and EAS as well as better understanding of how to optimise the programming may lower the need for programming changes.

Cochlear size is considered an important factor when deciding suitable electrode length [13]. In the present study, the patients with no post-surgery low-frequency hearing suitable for amplification were implanted with the longest electrodes (Flex28). The reason could be hearing deterioration due to a longer electrode or the choice of a longer electrode to a patient with less stable LFTs. An important issue is whether a short electrode should be replaced with a longer electrode to improve hearing if the patient loose low-frequency hearing. To avoid the dilemma of electrode replacement, nowadays at our clinic, longer electrodes are preferably used if the hearing preoperatively seems to deteriorate, and we do not replace an operating electrode. Van de Heyning et al. (2022) showed in their study that high hearing preservation rates can be obtained with both medium-length and longer electrode arrays. Implanting a longer electrode at primary surgery due to hearing deterioration over time and preventing the need for re-implantation was recommended. They also found that patients under the age of 45 had better hearing preservation than patients over the age of 45 when implanted with a medium length electrode [5]. The current study showed a statistically significant difference between electrode selection depending on age. The shorter electrodes were selected for the younger patients. It could be explained by hearing deterioration with age, but no correlation between surgical age and pre-surgery LFT PTA was found in our data. So, maybe it is an expression for lower risk-taking with the low-frequency hearing in younger patients. Nine out of the ten ears with pre-surgery LFT PTA ≥ 60 dB HL that were initially programmed with ES were implanted before 2015. Currently we would not offer EAS to that group of patients. We nowadays demand normal or near normal LFTs to consider EC or EAS and the LFTs should have been stable for several years to offer a short electrode. The purpose of CI-PDT is to use the EC or EAS for decades.

Recent studies have investigated the effects of providing a tonotopic match for the EC and EAS stimulation based on post-implantation radiological images. Fu and colleagues [14] conclude that tonotopic mismatch should be minimised to maximise the benefit of EAS hearing. A study by Dillon concludes that EAS users experience better initial performance when place-frequency mismatch is reduced [15]. Similarly, Di Maro found better speech discrimination outcome in patients with improved place-frequency map [16]. Also, better speech discrimination in noise and sound quality for speech and music were found [17]. As explained by Figure 1 the processor programming can be done in many ways and there are numerous not optimal ways to program the processor for EC and EAS. The problem when programming a processor is that one is not aware of the exact mismatch or overlap and different strategies to overcome this will be used. However, even aware of the programming challenge, it is not always straight forward for the patient to test a new programming after using one programming for many years. Many gets used to what they have, not noticing a slow deterioration of LFTs, and they are not always willing to try a new sound from a different programming, even though it probably would be beneficial. In Erixon and Rask-Andersen (2015) we showed that partially deaf patients receiving a CI-hearing gained better speech comprehension irrespective of preserved LFTs. This may explain the sometime unwillingness for the patient to switch form. The patient is often already satisfied with their hearing, that is way better than pre-surgery.

Since our first implantation of short electrodes in September 2008 there has been a change considering electrode lengths, pre-surgery candidacy and processor programming for EC and EAS at our clinic as well as from the implant manufacturers. Moreover, hearing aid technology (amplification, streaming possibilities etc.) has improved, and in many cases, postponing implantation. There are also novel demands on processor technology employed in symbiosis with contralateral hearing aid, for telephone streaming and mobile phone audio in recent years. This is the reality when introducing a new treatment for a group of patients and therefore comparison of results over time is limited. Still a reflection of the variable and challenging CI-PDT could lead to a better processor programming and selection of CI-PDT candidates.

Conclusion

To decide what programming form to use, and when to change it, can be challenging both for the clinic and the patient. Twenty-five percent of patients initially fitted with EC or EAS switched forms within two years. Twenty-one percent of the patients who switched between programming forms experienced difficulties adapting to the new programming. Further studies on how to choose the most beneficial sound processor programming parameters for EC and EAS, and when to change between programming forms, are warranted as well as clear guidance on choosing the right candidates for EC and EAS.

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Ethical approval

The study was approved by the Swedish Ethical Review Authority (Dnr 2023-00518-01). The Swedish Ethical Review Authority approved the study without informed consent.

Disclosure statement

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this paper.

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