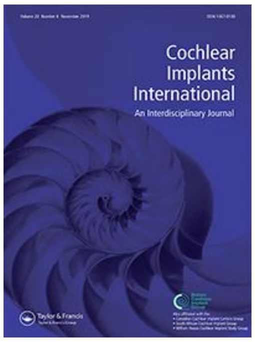

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Electric acoustic stimulation (EAS) with the Naída CI Q90 sound processor in experienced cochlear implant users

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Objectives: The benefit of using the electroacoustic functionality was tested compared to electric stimulation alone. Two different cut-off frequencies between acoustic and electric stimulation were tried.
Methods: Performance and subjective preference in 10 subjects was measured with electric only and electroacoustic stimulation with two settings: a cut-off for acoustic amplification at the frequency where thresholds exceeded 70 dB and 85 dB. An overlapping setting was also tried in five participants.
Results: There was a non-significant trend with a median improvement in SRT of 1.3 dB (70 dB cut-off) and 0.8 dB (85 dB cut-off) compared to the electric only condition. From nine subjects who completed the study, one preferred the 85 dB cut-off frequency, with the others preferred either a 70 dB cut-off or an overlapping setting.
Discussion: Nine subjects continued to use the EAS processor after study termination because of subjective benefits. The variability in speech outcomes and subjective preference is underlining the importance of being able to manually change acoustic and electric cut-off frequencies.
Conclusion: There were non-significant median group benefits from use of the acoustic component for these existing CI users. A hearing loss of 70 dB HL is an appropriate default cut-off frequency in the fitting software.

Keywords: Cochlear Implant, Fitting, EAS, Crossover Frequency, Hearing Preservation, MidScala Electrode

Introduction

In the early days of implantation, candidates for a cochlear implant (CI) were bilaterally profoundly deaf, with little or no residual hearing in either ear. As technology and the speech understanding performance of CI users have improved, the indication range for suitable CI candidates has been extended and the number of implantations in recipients with usable residual hearing in both ears has increased (Amoodi *et al.*, 2012; Krueger *et al.*, 2008; Wilson and Dorman, 2008). Many implant recipients are now fitted, as standard, with a hearing aid on the contralateral side in order to provide some degree of binaural hearing (Ching *et al.*, 2007; Morera *et al.*, 2012; Offeciers *et al.*, 2005). However, improvements in surgical technique and electrode array design have enabled surgeons to also preserve the hearing in the implanted ear of many of these users (Jurawitz *et al.*, 2014; Lenarz *et al.*, 2013; Skarzynski *et al.*, 2012). Lenarz *et al.* (2013) showed that, in a group of 60 prospectively recruited patients with some preoperative hearing and implanted with a reduced length Nucleus Hybrid-L24 electrode array, the group median increase in air-conduction thresholds in the implanted ear postoperatively for thresholds at 125–1000 Hz was <15 dB HL. Jurawitz *et al.* (2014) showed similar results, with a median postoperative loss of hearing at thresholds from 250–1500 Hz of

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10 dB HL for the Nucleus Hybrid-L24 and 19 dB HL for a longer electrode array (Nucleus CI422).

The traditional CI system provides access to a frequency range of around 200–8 kHz but, due to the length of the electrode array, electrical stimulation is not directly provided to the most apical region of the cochlea. A hearing aid also provides acoustic amplification across the frequency range and, when used in parallel, the two devices can work together to offer stimulation along the whole length of the cochlea. Acoustic amplification is delivered in the lower frequency range, where the inner hair cells are still receptive and electrical stimulation is provided in the higher frequency regions. There is good evidence to show that fitting an additional hearing aid on the ear ipsilateral to the cochlear implant to access any residual hearing can improve speech perception, localization and subjective sound quality, even if only a little usable low-frequency hearing remains (Gifford *et al.*, 2013; Incerti *et al.*, 2013; Lenarz *et al.*, 2013; Zhang, *et al.*, 2010). In a review of published papers, Incerti *et al.* (2013) reported that five out of six studies showed a benefit of ipsilateral electroacoustic stimulation over the CI alone of up to a 30% improvement in speech perception in noise. Five out of nine studies also showed a benefit in quiet, ranging from 4 to 15%. There has also been some inconsistent evidence that adding ipsilateral acoustic hearing improved performance compared to the bimodal listening condition with CI and contralateral hearing aid alone. Gifford *et al.* (2013) showed that, in a situation in which a diffuse noise field was present, using the ipsilateral acoustic hearing improved the adaptive signal-to-noise ratio by 1.8 dB. In contrast, Lenarz *et al.* (2013) found no significant benefit of adding ipsilateral acoustic stimulation to the bimodal condition for speech in quiet and speech in noise (speech and noise co-located from a frontal loudspeaker).

Electroacoustic sound processors are devices which combine a CI sound processor with acoustic amplification within one device, to allow easy access to both electrical and acoustic stimulation in the same ear (Helbig and Baumann, 2009; Lenarz *et al.*, 2013). Whilst there is reasonable agreement that the fitting of a hearing aid to the implanted ear of a CI recipient provides additional benefit, there is little agreement on how that hearing aid should be fitted (Ching *et al.*, 2015). In the currently published studies investigating different fitting options, the acoustic component was fitted using either the manufacturer's recommendations or a standard fitting prescription, such as National Acoustics Laboratory Non-Linear 1 (NAL-NL1). Researchers then explored the balance between acoustic and electrical stimulation across the frequencies and how much overlap, if any, there should be. Different experimental electrical settings were created by systematically altering the frequency allocation table used to change the low-frequency cut-off for the implant (Dillon *et al.*, 2014; Helbig *et al.*, 2011; James *et al.*, 2005; Karsten *et al.*, 2013). Dillon *et al.* (2014) showed that, in a small group of subjects, using the standard NAL-NL1 fitting prescription for the acoustic component improved results compared to the manufacturer's standard default. The implant frequency allocation was set so that electrical stimulation was provided for frequencies at which thresholds were at or above 65 dB HL. Karsten *et al.* (2013) and Vermeire *et al.* (2008) evaluated whether better results could be obtained when the full frequency range was provided by the implant, thus having an overlap between electrical and acoustic stimulation. However, both found that settings in which the frequency overlap was reduced or eliminated were better for speech perception in noise. Karsten's study of 10 adults tested settings in which electrical stimulation started with frequencies 50% above and 50% below the upper edge of the acoustic stimulation and found that both sounded less natural than when the electrical and acoustic stimulation met at the designated frequency. Vermeire *et al.* (2008) additionally investigated whether acoustic amplification should be limited so that there was no amplification provided at frequencies with thresholds over 85 dB HL. However, in their very small sample of four subjects, they found better results for the widest possible amplification range (Karsten *et al.*, 2013; Vermeire *et al.*, 2008). The change over point between the electrical and acoustic stimulation is called the cut-off frequency and is most commonly based on the subjects' audiograms, but varies greatly depending on the study. In Helbig and Baumann (2009), Gstoettner *et al.* (2008) and Vermeire *et al.* (2008), 65 dB HL was used as the cut-off frequency. This is considered to be the maximum loss attributable to the outer hair cells, and above this level amplification is considered to be no longer useful. However, other studies have used higher thresholds of 80 dB HL (Lenarz *et al.*, 2009) or even >90 dB HL (Gantz *et al.*, 2009). At this level a complete loss of inner hair cells is likely to have occurred leaving a dead region (Moore *et al.*, 1999). Karsten *et al.* (2013) chose not to use an arbitrary value based on the audiogram but set the cut-off to the frequency where real ear measurements came within 7 dB of the target. With the widely varying degrees of residual hearing in the study populations, this individualized setting of the low-frequency cut-off for electrical stimulation results in large variations across studies, with cut-off values reported from 250 Hz (Vermeire *et al.*, 2008) to 1760 Hz (Karsten *et al.*, 2013).

The Naída CI Q90 sound processor from Advanced Bionics (Valencia, CA, USA) combined with the acoustic ear hook can be fitted to any CI recipient, both existing and new, who has a C-II Advanced Bionics or later internal device. In the current software, acoustic amplification is set using a custom formula based on the Phonak Adaptive Digital Fitting formula. The cut-off between electrical and acoustic stimulation is set at the frequency where thresholds are 70 dB HL, considered to be the maximum aidable level as a dead region is likely to be present when the hearing loss is 70 dB HL or more (Moore *et al.*, 2010). However, some researchers also found that additional benefit could be gained from providing acoustic amplification at frequencies with thresholds up to 85 dB HL. Therefore, in the present study, two different electroacoustic fitting configurations were evaluated, with the frequency cutoffs set respectively at the frequency where residual hearing was 70 dB HL (the software default value) or 85 dB HL on the most recent audiogram. The primary aim of this study was to investigate if there was a significant benefit over the CI alone when the acoustic device was used with the 85 dB HL cut-off setting as well as the 70 dB HL cut-off for speech perception in noise and subjective perception in a group of existing adult Naída CI sound processor users. The secondary aim was to compare the benefit gained from the different cut-off frequencies for the acoustic component. Our clinical experiences with fitting these existing CI users with an electroacoustic speech processor are also reported.

Materials and methods

Subjects

Inclusion criteria for participation were:

- Preserved low-frequency residual hearing in the implanted ear (threshold ≤80 dB HL for at least one frequency),
- Usage of a Naída CI Q70 sound processor for more than three months,
- Ability to attend all study appointments and complete the study assessments.

Ten subjects matching those criteria were identified from the database who all agreed to participate. Two subjects were bilaterally implanted and each ear was fitted separately, but only speech perception results for the first ear were included in the analysis. Age at time of testing ranged from 38 to 80 years old with a median age of 60 years old and the duration of cochlear implant use ranged from 3 to 48 months with a median duration of 5 months. Unaided thresholds for all 12 ears are shown in Fig. 1. The low-frequency PTA (mean across 125, 250 and 500 Hz) ranged from 38 to 95 dB HL with a mean of 65 dB. At the first study appointment, the ten subjects were upgraded from their existing processor to the Naída CI Q90 processor with acoustic ear hook. Two of them had preserved hearing in both ears, resulting in 12 upgraded ears in total. The subjects' demographics are listed in Table 1.

Performance measures

Hearing thresholds at the first appointment were measured with a clinic audiometer KA450 (Zeisberg). Speech understanding in noise was assessed using the adaptive Oldenburg sentence test (OLSA) (Wagener *et al.*, 2006). Both speech and steady-state speech-shaped noise were presented from a loudspeaker placed at 1 m directly in front of the subject in a sound-proof room. The noise level was fixed at 65 dB(A) and, depending on the number of words that the subject understood, the speech level was varied adaptively until the speech reception threshold (SRT) for 50% speech intelligibility, expressed as signal to noise ratio (SNR), was reached. For each device condition, two lists were measured and their results averaged. Although the subjects were familiar with the OLSA test from their routine clinical tests, one practice list was performed at the beginning of each study appointment to minimize training effects.

To reflect the everyday use situation, the ipsilateral ear canal was not plugged in the electric stimulation only condition, so some subjects may have had some acoustic input, even without acoustic amplification. In contrast, if residual hearing in the contralateral ear was better than 60 dB HL at one frequency, this was plugged to only measure the performance of the ipsilateral ear. Bilateral subjects were tested with each ear separately; the contralateral processor was removed and the contralateral ear blocked if there was sufficient residual hearing. No acclimatization period was given for unilateral processor use.

Device fitting

The Advanced Bionics custom fitting software, SoundWave™, was used for programming the Naída CI Q90 processor. The clinically used setting was imported into the fitting software from the subject's current Naída CI sound processor and saved to the Naída CI Q90. All fitting parameters remained the same except for the T-Mic, used by all ten subjects, which was changed to the omni-directional processor microphone.

The subject's audiogram was entered into the software and the acoustic coupling set to PowerDome. The acoustic component was fitted using the AB-Phonak fitting formula provided in the software, which is based on modifications of the Adaptive Phonak Digital fitting formula to better align the hearing aid and CI fitting for bimodal use (Chalupper *et al.*, 2013). Traditional fitting

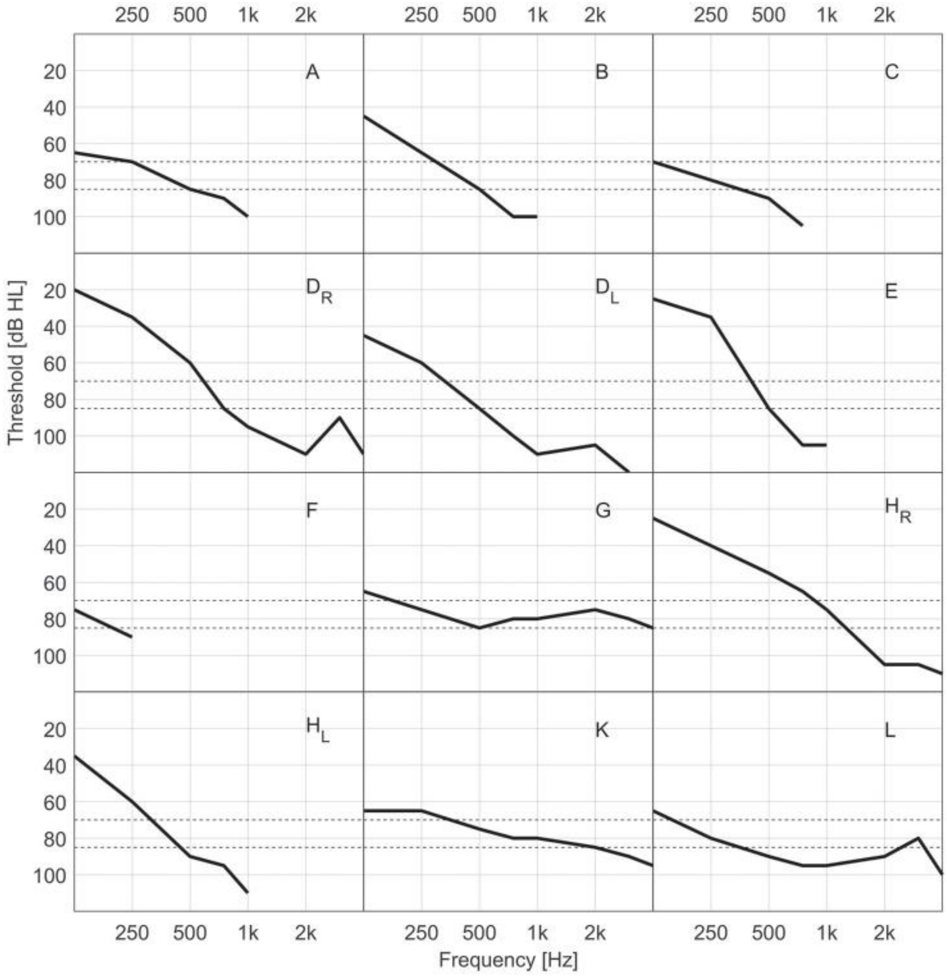

Figure 1 Hearing thresholds (dB HL) from 125 Hz to 4 kHz for each subject at date of first study appointment. For reference dashed lines are drawn at 70 and 85 dB HL.

prescriptions (e.g. NAL-NL2, DSL v5) focus on amplification in frequency regions that are important for speech understanding (1–4 kHz), whereas low frequencies (250–750 Hz) may be most important to maximize bimodal benefit (Sheffield and Gifford, 2014). Moreover, low compression knee points (<50 dB SPL) and moderate compression ratios (~2:1) are usually prescribed for hearing aids, while cochlear implants use very different input/output functions (e.g. Naída CI: compression knee point = 63 dB, compression ratio = 12:1). Finally, the dynamic behaviour of AGC systems differs substantially between devices. Hearing aids typically implement syllabic compression (attack/release time < 50 ms), whereas cochlear implants use slow-acting automatic volume control (attack/release > 1 s) (Veugen *et al.*, 2016). To address these issues, the AB-Phonak fitting formula comprises three main adjustments to the standard hearing aid fitting:

(1) The audibility of low frequencies is optimized by adjusting the low-frequency gain and bandwidth.
(2) Loudness growth is aligned by implementing the input–output function of the cochlear implant in the hearing aid (compression knee point = 63 dB SPL, compression ratio = 12:1).
(3) The dynamic compression behaviour is aligned by porting the Naída CI dual loop automatic gain control into the hearing aid (Veugen *et al.*, 2016).

Two settings were generated so that the frequency ranges of the acoustic stimulation and electric stimulation did not overlap. The cut-off frequency for the acoustic amplification was set at the frequency where

Table 1 Demographics of study participants. D_R/H_R and D_L/H_L are denoting the right and the left ear of subject D/H. 'Age' and 'Duration of CI use' are both in relation to the date of the 1st study appointment

Subject	Age [years]	Duration of CI use [months]	Implant
A	55	10	MidScala
B	44	5	MidScala
C	38	12	MidScala
D_R	60	5	MidScala
D_L	60	20	MidScala
E	62	5	MidScala
F	76	5	Helix
G	80	20	MidScala
H_R	39	48	1j
H_L	39	3	Helix
K	76	5	MidScala
L	60	5	MidScala

the hearing loss exceeded 85 dB HL (cut-off 85 dB) at the first visit and 70 dB HL (cut-off 70 dB) at the second visit. This cut-off frequency was then used as the starting frequency for the most apical electrode contact. Centre frequencies of the remaining electrodes were logarithmically interpolated to cover the full range between cut-off frequency and the standard centre frequency for the most basal electrode. By changing electric cut-off frequency, the assignment of environmental frequencies to the specific electrodes (frequency allocation table, FAT) was changed. If subjects complained about the change in sound quality due to a large change in the frequency-to-electrode assignment, the cut-off frequency was reduced step-by-step to reach an acceptable sound quality. The volume control of the processor was set so that the volume of both the electric and the acoustic stimulation were changed simultaneously when the processor buttons were used.

Study schedule

The study schedule, which included three appointments in the clinic and two three-week take-home periods, is illustrated in Fig. 2.

OLSA sentences were first measured with the Naída CI Q90 sound processor with the subject's current clinical setting in the electric-only condition. The cut-off 85 dB setting was then created and loaded onto the processor and the OLSA repeated with the newly fitted cut-off 85 dB settings, without any acclimatization. After three weeks take-home experience with the cut-off 85 dB setting, subjects were tested again using the OLSA. At the end of this session, the processor was reprogrammed with a cut-off 70 dB setting and a further three weeks take-home experience given with the cut-off of 70 dB. Three weeks later, at the third appointment, the OLSA sentences were repeated with the cut-off 70 dB setting. For five subjects, a third fitting was tested at the third appointment. For this fitting the acoustic cut-off frequency was set to the frequency where the hearing loss exceeded 85 dB HL and the electric cut-off to a hearing loss of 70 dB HL, resulting in an overlapping setting ('Overlap 85/70'). Because the electric filterbank for this setting is the same as for the cut-off 70 dB condition, it was assumed that no acclimatization period was required and testing was completed directly after the fitting. At the end of the last appointment subjects were asked for their preferred fitting, which was then programmed onto the processor for daily use and any subjective comments or feedback on the sound quality of the electroacoustic processor collected. All subjects tried the settings in the same order, with no randomization of conditions which is a weakness in the study design.

The study was approved by the local Ethical Committee (Charité Medical School, EA 1/085/15).

Statistics

Non-parametric statistical analyses were used to compare three dependent conditions (clinical setting vs. cut-off 70 dB setting, clinical setting vs. cut-off 85 dB setting and cut-off 70 dB setting vs. cut-off 85 dB setting) with a Wilcoxon paired test. A corrected alpha divided by the number of pairwise comparisons was used, leading to an alpha value of 0.0166. Therefore, tests were considered statistically significant when the corresponding P-value was less than 0.0166.

Because the ability to fuse the electric and acoustic input might be influenced by cognitive abilities, only the first implanted ears of the bilateral subjects were included in the statistical analysis.

Results

All subjects were upgraded to the Naída CI Q90 processor with acoustic ear hook. The overall hearing aid gain (over all input levels and frequencies) was changed in three subjects to achieve a comfortable sound: subject B: overall gain decreased by 5 dB; subject H_R and D_R: overall gain was increased by 3 dB. Fine tuning in all other subjects was not necessary. At the first fitting, many subjects reported a significant change in voice quality (robot-like or squeaky voices) when the FAT for electrical stimulation was altered. For most subjects, this was not acceptable for the three-week take-home experience and the computed cut-off point, based on the audiogram, was lowered gradually for each individual until the subject reported acceptable sound quality.

Subject G was not able to acclimatize to the new processor, stopped using it and dropped out of the study after the second appointment. Therefore, he was excluded from statistical analysis, giving an n of 9 subjects for each setting (Fig. 3).

Table 2 shows the computed and the fitted cut-off frequencies for all three settings. Only one subject took the computed setting home on their processor (subject A for the cut-off 70 dB fitting), with two subjects requiring a large change to the computed frequency (subjects H_R and K). For the subjects considered in the statistical analysis, the resulting adjustments produced a mean cut-off frequency for the cut-off 85 dB fitting of 422 Hz ± 148 and for the cut-off 70 dB fitting of 302 Hz ± 92. For six subjects the lower frequency boundary for the cut-off 70 dB fitting and standard clinical fitting were the same (A, B, C, E, F, L). For three subjects the adjusted cut-offs for cut-off 85 dB and cut-off 70 dB fittings were the same (L and F; 250 Hz and D_L; 350 Hz).

At the initial fitting session, speech perception performance for the group was poorer when the newly

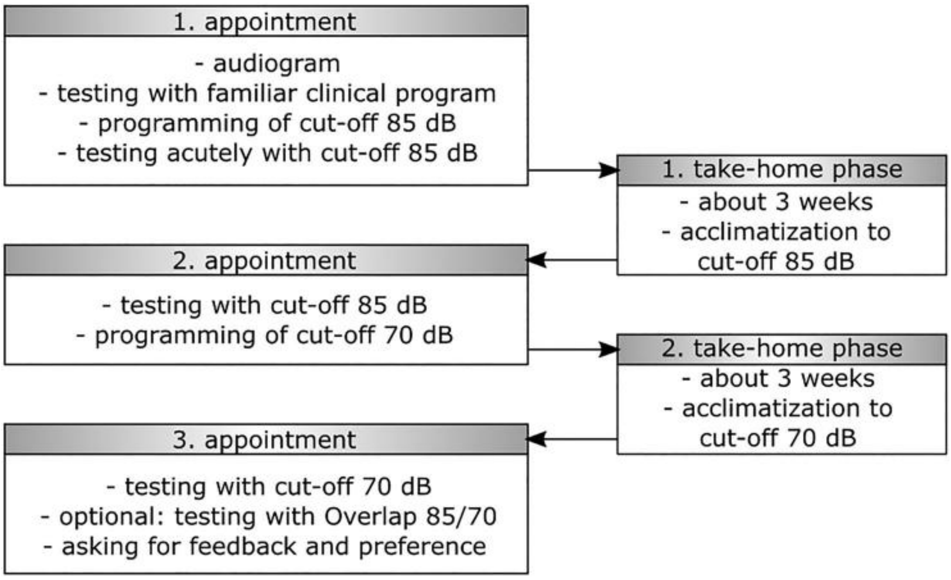

Figure 2 Study schedule.

adjusted cut-off 85 dB setting was tested, with the median SRT increased compared to the standard clinical fitting. After three weeks of acclimatization with the cut-off 85 dB median, SRTs were 1.3 dB lower compared to the clinical setting but this difference was not statistically significant (Wilcoxon Matched Pairs test with a corrected alpha value; $T = 13$; $Z = 1.1$; $p = 0.26$). After fitting and use of the cut-off 70 dB setting, there was an improvement in median SRT compared to the clinical setting of 0.8 dB (Fig. 3), which was not significant either ($T = 4$; $Z = 2.2$; $p = 0.028$). There was no significant difference between the cut-off 85 dB and cut-off 70 dB fitting configurations ($T = 18$; $Z = 0.53$; $p = 0.59$). The Overlap 85/70 for the five tested subjects (A, D_L, H_R, K, L) produced the lowest median SRT score of −2.2 dB compared to a median value of 0.3 dB for the same five subjects for the cut-off 70 dB setting, tested in the same session, and 1.35 dB for the clinical setting tested at the start of the study.

Individual differences in SRT between EAS settings and the clinical setting for the 12 ears are depicted in Fig. 4. Results at 0 dB indicate equal performance to the clinical setting. As can be seen, most of the data points lie in the positive range, showing an improvement or similar performance with use of the electric

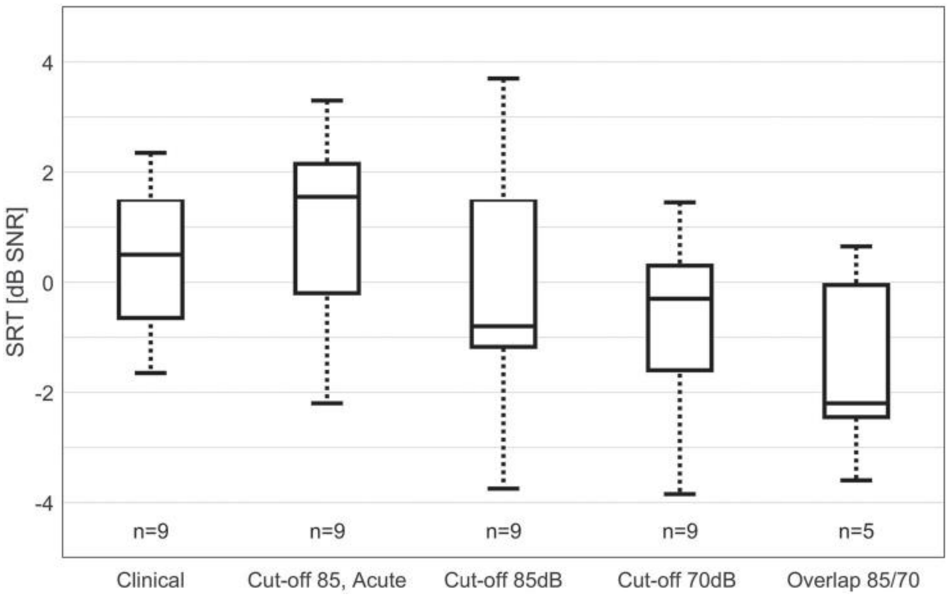

Figure 3 Boxplots showing the group SRTs achieved for the adaptive OLSA sentences for the different device conditions. Clinical testing was done with the Naida Q90 at the start of the study, with electric only stimulation. Subsequent tests are done with electrical and acoustic stimulation (E + A) using the acoustic earhook. The boxes represent the quartiles, whiskers show the range of data points and the line in the box indicates the median value. There were no significant differences between the cut-off 85 dB, cut-off 70 dB and clinical setting (Wilcoxon Matched Pairs test).

Table 2 Computed and fitted cut-off frequencies for electrical stimulation for clinical, cut-off 85 dB and cut-off 70 dB settings. Also indicated is the hearing loss at the fitted cut-off (interpolated from subject's audiogram). Each subject's preferred setting at the end of the six-week trial, if available, is indicated in the last column on the right. Bold highlighted subjects were considered for statistical analysis

		Cut-off 85 dB			Cut-off 70 dB			
	Clinical Fitting	Computed	Fitted	HL @ fitted cut-off	Computed	Fitted	HL @ fitted cut-off	Preferred fitting
A	250	500	350	76	250	250	70	Overlap
B	250	500	520	86	312	250	65	85dB
C	250	375	350	84	125	250	80	70dB
D_R	250	750	520	62	600	350	45	
D_L	250	500	350	70	333	350	70	70dB
E	250	500	520	87	425	250	35	no preference
F	250	208	250	90	208	250	90	no preference
G	250	500	350	79				
H_R	250	1333	690	63	875	520	56	70dB
H_L	250	458	520	90	333	350	72	
K	250	2000	520	75	375	350	69	70dB
L	250	375	250	80	166	250	80	Overlap

acoustic stimulation (EAS) compared to electrical only stimulation. Subject A performed slightly worse with both EAS settings and Subject E was an outlier, with much worse performance with the cut-off 85 dB setting compared to the clinical setting.

At the end of the study, the patient's preferred setting and any subjective comments on sound quality were recorded. The subjective reports indicate improved listening with the EAS condition (Table 3). One subject (G) reported poor sound quality with the EAS mode and reverted back to their Naída CI Q70 with T-Mic after the cut-off 85 dB testing, before the end of the study period. Speech perception performance, however, was better with the EAS fitting compared to the clinical setting.

Discussion

Although, on average, there were no significant benefits for this group of existing CI users, most subjects preferred the sound of the EAS setting against the clinical setting. Only one subject did not choose to keep the EAS mode, mainly due to discomfort problems with wind noise as a result of changing to the omnidirectional microphone. Although the SRT

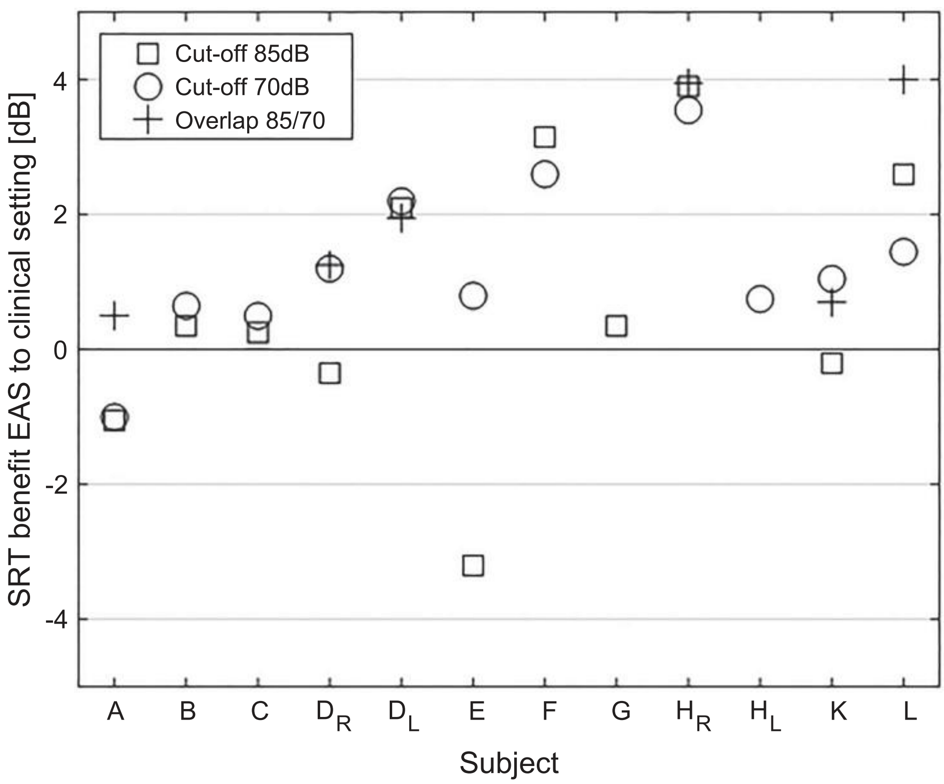

Figure 4 Individual benefits in SRT for different EAS settings. Positive values indicate an improvement with the EAS setting, negative values a deterioration.

Table 3 User comments about their experience with the Naída CI Q90 EAS sound processor, at the end of the study period

A – spontaneously pleasant hearing sensation, everything more distinct	B – better speech understanding in noise and self-perception while singing
C – more distinct, low frequency voices clearer	D – speech understanding better, more natural hearing (music)
E – more natural, spatial sound	F – speech understanding in noise better
G – not better, hears additional crackling and rustling	H – spontaneously distinct better speech understanding
K – own voice more natural, the high pitched sound is gone	L – better, more rounded sound

benefits are usually small (around 1–3 dB), it is expected to provide a noticeable clinical improvement for speech understanding in noise and was comparable to the improvements reported in other studies (Gifford *et al*., 2013; Lenarz *et al*., 2013). However, due to the fixed order of the test conditions, learning effects were not controlled for and some subjects might have continued to improve, regardless of the addition of the acoustic component, especially those with less than nine months of implant use. At the same time, there are also potential limitations in the study design showing the full advantage of the added acoustic stimulation. It was previously shown that more difficult noise condition, such as a diffuse noise field or competing talkers, are more appropriate to reflect the everyday benefits of ipsi- or contralateral acoustic stimulation than the setup used in this study (Gifford *et al*., 2013; Veugen *et al*., 2016). Also some subjects had access to unaided acoustic hearing for the electric stimulation only testing, as the ipsilateral ear was not blocked during testing. This may have improved scores for these subjects in the clinical condition and reduced the difference between the electric acoustic conditions and the electric only condition. Subjects were also tested without their contralateral ear, which has been shown to provide significant additional benefit when combined with electroacoustic stimulation in the ipsilateral ear (Dunn *et al*., 2010; Gifford *et al*., 2010).

The results of the subjective reports support the objective findings with nine out of the ten subjects reporting benefits when using the acoustic component for overall sound quality, speech perception in noise and, for one subject, music. However, because all subjects had used Naída CI Q70 sound processors with the T-Mic, some found transferring to an acoustic ear hook and omnidirectional microphone hard. This was especially noticeable with wind noise and when using the telephone. Nonetheless, nine out of the ten subjects chose to keep their new sound processors with acoustic ear hook at the end of the study.

When the initial fittings were created, the change in FAT resulted in a noticeable change in the overall sound perceived. In this study, the clinician was given the option to adjust the prescribed frequency boundary based on subject feedback. This was introduced because, unlike subjects in other studies such as Vermeire *et al*. (2008) and Karsten *et al*. (2013), subjects were not existing EAS users who were familiar with an EAS setting. All subjects had been using a standard CI sound processor for a minimum of three months (group median five months). This provided them with a full standard frequency allocation to a standard length electrode array, to which they had become accustomed. Changing the FAT alters the place frequency map and can produce temporary changes in sound quality, to which the brain needs time to adapt (Reiss *et al*., 2012). When the initial fittings were created, the place pitch allocation was changed, especially in the cut-off 85 dB setting, and produced a noticeable change in the overall sound perceived. This change was sufficient in all 12 ears to prompt the clinician to alter the computed lower frequency boundary in the cut-off 85 dB fitting. In the cut-off 70 dB fitting the changes resulted in the frequency allocation returning to the clinical FAT in six out of 11 ears. This resulted in a very small difference in mean cut-off frequency between the two fitting prescriptions of 121 Hz and made it hard to make any meaningful comparison between them. It would seem that, in this group of converted users, subjects tended towards favouring the original clinical FAT, but if subjects had been encouraged to try the original cut-off 70 dB and cut-off 85 dB fitting for longer before making any change, they may have been able to adapt to it and benefited longer term. This is in contrast to Karsten *et al*. (2013), who found that subjects did not necessarily prefer the experimental setting that was closest to their clinical setting, although subjects in that study all had a reduced length electrode array and were all already using an EAS sound processor.

Examination of the computed and fitted cut-off frequencies shows that most subjects preferred a greater range of electrical stimulation at lower frequencies than either the cut-off 70 dB or 85 dB fittings predicted. At the end of the study only subject B chose the cut-off 85 dB fitting with the higher low-frequency cut-off, all others chose the fitting with the lowest low-frequency electrical cut-off. It could be argued that subjects with less residual hearing would opt for more complete electrical coverage, but there was no obvious pattern between the amount of residual hearing and the subjective preference. Karsten *et al*. (2013) also found that optimal allocations did not depend upon degree of low-frequency residual hearing. For four subjects in our study group an unrestricted electrical bandwidth was still the preferred option, a finding also reported by Kiefer *et al*. (2005) and Fraysse *et al*. (2006), who also used standard length electrode arrays.

An overlapping setting was the preferred fitting for two out of the five subjects who tried it and produced the lowest median SRT scores overall. Studies showing reduced scores in noise for overlapping fittings involved subjects using reduced length electrode arrays (Karsten *et al*., 2013). In other studies using standard length electrode arrays, an overlap between acoustic and electrical stimulation has not necessarily been detrimental (Baumann and Mocka, 2017; Kiefer *et al*., 2005). There is clearly considerable variation in individual performance and this overlapping setting should not be ignored as a clinical option for some subjects.

The subjects in this study were all converted from a standard CI processor, so it is unknown if these results could be generalized to new CI users first switched on postimplantation with an EAS processor.

Conclusions

Existing CI users with usable residual hearing can benefit from converting to an electroacoustic sound processor. Nine out of ten subjects continued to use the EAS sound processor after the study period and one subject rejected the EAS processor and preferred to continue to use the clinical processor with T-Mic. Only one out of the nine subjects preferred the 85 dB HL cut-off frequency, with the others preferring either a 70 dB HL cut-off frequency or an overlapping setting or having no preference. There was no difference in speech perception scores between the cut-off 70 and 85 dB fittings. Based on these results, the default cut-off fitting of 70 dB HL in the SoundWave software is a reasonable starting point for fitting the Naída CI Q90 processor with acoustic ear hook for existing users of the Naída CI Q70 sound processor. For these existing users, the 85 dB HL cut-off frequency fitting required too big a change in frequency allocation to be tolerated, but with longer acclimatization this change may become acceptable and provide better results for some individuals. For some users an overlapping setting with a standard electrical frequency allocation may be the preferred option. The results of this study also highlight the importance of making individual adjustments, to provide users with an optimal set of parameters to maximize benefits.

Disclaimer statements

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Conflicts of interest We would highlight the fact that the third author is employee of Advanced Bionics, the manufacturer of the device under investigation in this report.

Ethics approval None.

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