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Technical Report

Experiences of the use of FOX, an intelligent agent, for programming cochlear implant sound processors in new users

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Abstract

Objective. This report describes the application of the software tool “Fitting to Outcomes eXpert” (FOX) in programming the cochlear implant (CI) processor in new users. FOX is an intelligent agent to assist in the programming of CI processors. The concept of FOX is to modify maps on the basis of specific outcome measures, achieved using heuristic logic and based on a set of deterministic “rules”. *Design.* A prospective study was conducted on eight consecutive CI-users with a follow-up of three months. *Study Sample.* Eight adult subjects with postlingual deafness were implanted with the Advanced Bionics HiRes90k device. The implants were programmed using FOX, running a set of rules known as Eargroup’s EG0910 advice, which features a set of “automaps”. The protocol employed for the initial 3 months is presented, with description of the map modifications generated by FOX and the corresponding psychoacoustic test results. *Results.* The 3 month median results show 25 dBHL as PTA, 77% (55 dBSPL) and 71% (70 dBSPL) phoneme score at speech audiometry and loudness scaling in or near to the normal zone at different frequencies. *Conclusions.* It is concluded that this approach is feasible to start up CI fitting and yields good outcome.

Sumario

Objetivo: Este reporte describe la aplicación del programa-herramienta “Fitting to Outcomes eXpert” (“eXperto en adaptación por resultados”) (FOX) en la programación de procesadores de implante coclear (IC) para usuarios nuevos. El concepto de FOX es modificar los mapas sobre la base de medidas específicas de resultados, logradas usando una lógica heurística y basado en un grupo de “reglas” determinísticas. *Diseño:* Se condujo un estudio prospectivo en ocho usuarios consecutivos de CI con un seguimiento de tres meses. *Muestra Del Estudio:* Ocho sujetos adultos con sordera post-lingüística fueron implantados con el dispositivo Advanced Bionics HiRes90k. Los implantes fueron programados usando el FOX, usando un grupo de reglas conocidas como consejo EG910 del EarGroup, que presenta un grupo de “automapas”. Se presenta el protocolo empleado para los primeros 3 meses, con descripción de las modificaciones de los mapas generados con FOX y los resultados de las pruebas psicoacústicas correspondientes. *Resultados:* La mediana de los resultados a 3 meses muestra un PTA de 25 dB HL, puntajes de fonemas en la logoaudiometría de 77% (55 dB SPL) y 71% (70 dB SPL), y una escala de intensidad subjetiva dentro o cercana a la zona normal en diferentes frecuencias. *Conclusiones:* Se concluye que este enfoque es factible para iniciar la programación de un CI y que brinda buenos resultados.

Key Words: Cochlear implant; Behavioural measures; Instrumentation; Speech perception

Currently available commercial cochlear implant (CI) systems share many common features. All consist of an external (usually ear-level) sound processor which processes the incoming microphone signal and converts this to a command stream which is delivered to an internal receiver via a radio link through the intact skin. The internal receiver is surgically implanted in the mastoid bone and is connected to a silastic electrode array which is inserted into the scala tympani of the cochlea, at or near the round window. The array supports several electrode contacts which are designed to stimulate individual populations of spiral ganglion cells along the cochlea. Low frequency information is directed to electrodes placed apically, and high frequency information to basal electrodes, thus preserving the natural tonotopicity of the cochlea.

Following surgical placement of the internal components, the external sound processor must be adjusted (‘programmed’) by the audiologist so that the characteristics of the stimulating current match the requirements of the individual. There are many processing parameters that can be adjusted, but the most commonly used are the output limits of the stimulating current. This is because the minimum current required to elicit an auditory percept, and the current where the percept becomes uncomfortably loud, are known to vary between individuals, and between electrodes in a given individual, due to several factors including local neural survival and the exact position of the electrode contacts.

Therefore, before the CI can be used to deliver a signal in response to microphone input, these current limits must be programmed for

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Abbreviations

FOX	Fitting to Outcomes eXpert
SIR	Speech intelligibility ratings

each electrode, so that stimulation is always within the comfortable range for the user. This is usually performed by presenting short current pulse trains at varying current levels in order to identify the threshold and the maximum comfortable level psychophysically for each electrode. The initial 'fitting' session usually involves setting these levels and possibly also checking whether any individual electrodes need to be deactivated, usually due to high thresholds or production of non-auditory sensations. This process is straightforward, though time consuming, in adults, but is far more difficult with young children, and it sometimes takes several fitting sessions to identify these current levels for all electrodes.

Once the set of programming parameters ('map') has been defined and downloaded to the sound processor, the user can start to use the CI. However, a process of adaptation to the electrical signal usually occurs over the first few weeks or months of device use, such that initially loud sounds become perceptibly quieter as the user becomes accustomed to the new signal (Walravens et al, 2006). As a result, the current limits usually have to be increased gradually in order to accommodate to this change. This can be achieved, in part, by volume control adjustment, or by having several maps loaded into the processor with different current limits. However, additional fitting sessions are usually required so that the audiologist can repeat psychophysical measurements and optimize the user's everyday map.

Thus, adjustment to the parameters of the map is usually based on comfort, with the assumption that the most comfortable map will also be optimal in terms of performance.

Performance is normally monitored periodically (primarily by speech recognition measures), but performance outcomes do not usually result in review of the map parameters unless the CI user is performing considerably poorer than would normally be expected. Expectations, however, tend to be rather imprecise, as it is well known that the performance of CI users varies greatly, even among relatively homogeneous subject groups (Roditi et al, 2009). Unfortunately, the most comfortable map is not necessarily the one that provides the best performance, a finding which is well known and documented in hearing aids (Schaub, 2010). Furthermore, a revised map may well result in a decrement of performance initially, so that many protracted trials may be required before map parameters can be optimized.

A particular concern with respect to the usual fitting procedure is its validation. Electrical stimulation at a single electrode or even a group of electrodes produces an electrical field which does not correspond to any physiological acoustic stimulation of the system. T and C levels may substantially differ depending on which procedure was used to set them. It can be questioned whether the minimal and maximal levels identified in this way truly represent the optimal stimulation zone of the subject once the full array is active (Willeboer & Smoorenburg, 2006). This is especially the case in subjects who may have never heard before, who have been deprived of hearing for a long period of time, or in children.

With these considerations in mind, we have developed an alternative approach to processor adjustment, which is based on specific outcomes, rather than comfort. Our method has involved the development of an intelligent agent known as the 'Fitting to Outcomes eXpert' or FOX. This report describes some early experiences and outcomes of using the FOX software tool in routine fitting of postlingually deafened recipients of the Advanced Bionics CI system.

The principles and mode of operation of FOX are described in detail by Govaerts et al (2010). Briefly, FOX considers results of several specific performance measures that reflect cochlear function and resolution and assesses whether the parameters of the map in use can be adjusted to improve these measured outcomes. The output of FOX consists of recommendations for any map modifications that it considers are required. The decision process employs heuristic logic and is based on a set of deterministic 'rules' derived from theory and experience (often trial and error) which is called an 'advice'. To date the only existing advice is the Eargroup's advice, which has been developed by analysing maps and performance measures from over 600 CI users implanted at our centre (Eargroup) over several years. The set of rules currently in use constitute Eargroup's EG0910 advice, but FOX is able to work with other sets of advice rules that may be developed in the future or by other centres. An advice would typically contain hundreds of conditional rules and rule sets. The detailed structure of the rule set of an advice is not disclosed as it is subject to intellectual property.

The performance measures currently utilized by FOX are: (1) free field audiometry (250 Hz to 8000 Hz), (2) A§E phoneme discrimination (Govaerts et al, 2006), (3) A§E loudness scaling at 250 Hz, 1000 Hz, and 4000 Hz, and (4) speech audiogram, using monosyllabic words at intensities from 40 to 85 dB SPL. Further details of these tests are provided in the methods section below. Map parameters considered by FOX are not restricted to threshold (T) and maximum comfortable level (M), but also include input dynamic range (the minimal and maximal sound levels between which the speech processor processes sound), electrode deactivation, gain (post-processing amplification applied to the signal), processing strategy, pulse rate, and bandpass filter boundaries.

One key feature of FOX is the availability of a set of 'automaps', which are designed to be used for the initial CI activation ('switch on'), before outcome measures are available. The parameters of these automaps are based on features of a large number of 'green' maps that have yielded outcomes that FOX considers optimal. There is a growing set of green maps and the statistics of this set form the basis for the parameters of the automaps. Based on these green maps, an incremental series of 10 automaps is created that may be used over the first few months, within a protocol such as that described in the methods section below. As the CI user progresses through the series, the T and M levels are incrementally increased as a proportion of those levels used in all available green maps. Other processing parameters remain constant throughout the automap series. The concept of an incremental series of preset maps was already proposed by others (e.g. Almqvist, 2004: The Almqvist/Lund procedure for adjusting a speech processor for a congenitally deaf child using objective measurements, Cochlear Nucleus Report, July/August, 3–4). But their preset fittings were based on the profile of the ECAP thresholds. Smoorenburg and colleagues argued however that the relation between ECAP thresholds and behavioural responses is not strong enough to allow for an accurate prediction of behavioural T and C levels in individual CI users (Willeboer & Smoorenburg, 2006; Abbas, 2006). This correlation appeared to be stronger in children and also in more recent publications, but it can be argued that this may result from a circular procedure, where the map-levels are first set based on ECAP thresholds resulting in a stronger correlation between both.

The aim of the present study was to use the FOX system to program the sound processor in a group of new users of the Advanced Bionics (AB) HiRes90k device over the first three months, focusing on the use of the automap feature, and to document performance outcomes and the map modifications recommended by FOX.

Methodology

Subjects

Eight consecutive subjects who received an AB HiRes90k device between June and December 2009 entered the study. They were all postlingually deafened, showed good speech production prior to implantation with speech intelligibility ratings (SIR) of 1 or 2 (Cox & McDaniel, 1989), and all but one used a hearing aid in at least one ear. No re-implantations were included and all subjects had full electrode insertion according to the surgical report.

Key demographics for each subject are provided in Table 1. Implantation was performed at an average subject age of 59 years (range 13–76 years). Surgery was performed by four different surgeons. Three subjects received the implant in the right ear, five in the left ear.

Characteristics of 'automaps'

For this study FOX 1.1 was used with Eargroup's EG0910 advice (further referred to as FOX1.1$^{(EG0910)}$).The 10 automaps are called 'Switch on', then 'Silver 1, 2, 3', 'Gold 1, 2, 3' and 'Ivory 1, 2, 3'. The switch-on map has T- and M-levels set to 20 and 90 current units respectively. The statistical basis for the incremental increase in T and M levels for the other automaps is outlined in Table 2. Essentially, there is a gradual increase in these values as a percentage of the 'ideal' parameters as defined by those identified from our green maps. Subjects were randomly assigned to one of two processing strategies, HiRes or HiRes 120. This approach is part of a further study comparing these two strategies, but does not impact on the process or outcomes of the present study.

Performance measures

FREE-FIELD AUDIOMETRY

This was carried out in a sound-treated audiometric room using a Madsen Aurical system (GN Otometrics) with free-field loudspeaker outputs calibrated to dB hearing level. The loudspeaker was positioned at 0° azimuth, 1-m from the subject's head. Thresholds to warble tones at 125, 250, 500, 1000, 2000, 4000, and 8000 Hz were recorded using standard clinical audiometric methods.

A§E PHONEME DISCRIMINATION

The A§E test suite is loaded onto the same PC as that running the Aurical system. Output is fed to the AUX input of the Aurical. The phoneme discrimination module is a discrimination test based around 20 pairs of vowels and consonants, which can provide a clinical indication of the frequency discriminating power of the auditory system. Discrimination of all 20 phoneme contrasts of the 'Eargroup's list' was measured at 70 dB SPL. Full details of calibration and test procedure are provided by Govaerts et al (2006).

A§E LOUDNESS SCALING

This is a loudness scaling procedure where narrow band noise of 250, 1000, or 4000 Hz is presented at different intensities (5-dB steps presented at random between two limits). The limits are set during a training session to just below the lowest audible level and just below the level which is too loud for the subject (typically about 20 and 90 dB SPL). The 1876 ms stimulus is presented at least twice at each presentation level, and the subject is required to indicate loudness using a seven-point visual-analogue scale, ranging from 'inaudible' to 'too loud'. The median score at each presentation level is recorded at the end of the test. A 'loudness index' was calculated for each test, which is the RMS-value (root mean square) of the scores compared to the average score at the same intensity in normally hearing listeners. A sign (positive or negative) was applied to this score, according to the sign of the sum of all differences between each of the subject's score and the corresponding average in hearing listeners. The average RMS in hearing listeners is 0 with a 95% confidence interval of -0.8 to $+0.8$ (from our own unpublished data). A RMS value of -1.1, for example, indicates an abnormal loudness scaling with more scores lower than the average in hearing listeners.

SPEECH AUDIOGRAM

Open set monosyllabic CVC-words (NVA-lists, Wouters et al, 1995) were presented at 40, 55, 70, and 85 dB SPL, using the same room and equipment as above. Two lists of 12 words were used at each intensity level and phoneme scores recorded.

FOX implementation

The FOX software is installed on several computers within a local area network, as is the Soundwave fitting software and the A§E and Audiqueen software. FOX is able to interface seamlessly between these modules in order to read outcome measures and implement required map modifications.

Automaps are automatically generated when a new CI-subject is entered into FOX. If accepted by the audiologist, they are permanently saved in the Soundwave fitting software and can be loaded to the sound processor as with any maps generated by other means. When output measures are available, FOX generates recommendations for map modifications which can be either accepted or rejected by the audiologist. If accepted, then FOX automatically implements the required modifications and activates the new map. Full details are provided by Govaerts et al (2010).

Table 1. Subjects demographics.

Subject	*Birth date*	*Etiology*[1]	*Preop PTA CI-ear*	*Preop imaging*	*Preop hear aid*
1	4/06/1938	Menière's	102	normal	contralateral
2	10/10/1969	Sudden idiopathic	120	normal	contralateral
3	26/01/1987	Progressive idiopathic	95	normal	bilateral
4	2/04/1996	Early acquired idiopathic	100	normal	bilateral
5	13/09/1933	Otosclerosis	118	otosclerosis	bilateral
6	2/03/1941	Otosclerosis	120	otosclerosis	ipsilateral
7	3/06/1961	Menière's	80	normal	No
8	11/10/1933	Progressive idiopathic	93	normal	bilateral

Table 2. Statistical basis for T and M levels used in the automap series.

Name	*Statistical basis*
Switch-on	Flat map with T-levels at 20 CU and M-levels at 90 CU
Silver 1	All variables are set between their value in the switch-on and in the Gold 1 map, at 1/4th of the interval
Silver 2	All variables are set between their value in the switch-on and in the Gold 1 map, at 2/4th of the interval
Silver 3	All variables are set between their value in the switch-on and in the Gold 1 map, at 3/4th of the interval
Gold 1	P25: All map-variables have values corresponding to the 25th percentile of the population of green maps
Gold 2	P50: All map-variables have values corresponding to the 50th percentile of the population of green maps
Gold 3	All variables are set between their value in the Gold 2 and in the Ivory 1 map, at 1/2nd of the interval
Ivory 1	P75: All map-variables have values corresponding to the 75th percentile of the population of green maps
Ivory 2	All variables are set between their value in the Ivory 1 and in the Ivory 3 map, at 1/2nd of the interval
Ivory 3	P97: All map-variables have values corresponding to the 97th percentile of the population of green maps

Fitting and assessment protocol

All subjects were fitted with the AB Harmony sound processor and were randomly allocated to either the HiRes or the HiRes coding strategy. The procedure was the same for all subjects and made use of the incremental series of automaps. This has been the routine clinical procedure for all CI users in our centre for several years and was not modified for this study. The following provides a step-by-step sequence of the procedures carried out:

1st session (S1)

- The first ('switch on') automap was activated in 'live mode'. As long as this was tolerated by the subject then the rest of the session was spent counselling the subject regarding operation of the external hardware and aspects of early device use.
- At the end of the session the subject received two sound processors. One was a loan processor containing maps Silver 1-2-3 and the other was the subject's own processor containing maps Gold 1-2-3. The subject left the clinic with map Silver 1 active and was instructed to change to the next map every 2–3 days as long as the auditory percept was comfortable.
- This session typically lasted 30–60 minutes, most of which was spent on counselling and familiarization. No performance testing was carried out.

2nd session (S2), typically two weeks after switch-on

- The aim of the second session was to identify any electrodes that may require deactivation. FOX can efficiently perform this task using the results of free field audiometry, but it is important to involve a competent audiologist to make judgments on any electrodes that produce non-auditory stimulation, usually involving the facial nerve (Niparko et al, 1991).
- The audiogram was performed and the results entered into FOX. Impedance telemetry measures were also performed at this point. FOX decided whether or not any electrodes require deactivation and provided appropriate suggestions.
- At the end of the session the subject was given the same map he/she came in with (with or without deactivated electrodes) with either one lower and one higher, or with two higher automaps in the three memory slots of the processor (depending on discussions with the subject) and the subject was instructed to try to assess the relative comfort of these maps over the following two weeks. The aim in this period was mainly to assess the most comfortable map, rather than trying to increase the levels.
- This session typically lasted 15–20 minutes.

3rd session (S3), typically four weeks after switch-on

- The primary aim of this session was to optimize the subject's preferred automap using the audiogram and A§E phoneme discrimination performance measures. These tests are detection and discrimination tasks, which we consider do not exhibit significant learning effects.
- Free-field audiometry and the A§E phoneme discrimination test were conducted as described above, and the results were input into FOX, which analysed the parameters of the map being used and formulated recommendations to modify the map in an attempt to improve the test results if appropriate. If map modifications were requested by FOX, then the performance tests were usually repeated. If FOX does not recommend map changes (either initially or after map modifications) it outputs a message suggesting that the fitting is 'optimal'.
- When FOX had no further recommendations, the subject was sent home with the optimized map. The previous map was also provided as a back-up, but the subject was strongly encouraged to use the new map as much as possible. This session typically lasted 30 minutes.

4th session (S4), typically two-and-a-half to three months after switch-on

- The aim of this session was to modify the subject's everyday map based on results from A§E loudness scaling and speech audiometry. The latter two tests are identification tasks, which we believe are subject to learning effects and changes over time. If the S3 results had not been optimal, FOX would have requested to also repeat free field audiometry or A§E phoneme discrimination if indicated.
- As in the former session, FOX analysed the map parameters and the test results and formulated recommendations for map modifications, if indicated, until no further testing was requested ('optimal' map assessed by FOX). If the session ended without having obtained 'optimal' results according to FOX, then the latest modifications were saved into the processor and the pending outcome requests (PORs) were retained for the next session, which was typically scheduled after another three months.
- This session typically lasted 60 minutes.

Results

The median interval from surgery to switch-on (S1) was 21 days (range 17–22), and the intervals from switch-on to S2, S3, and S4 were 11 (7–16), 28 (21–42), and 78 (46–111) days respectively.

Table 3. Automaps in use by each subject at the start of sessions S2, S3, and S4, plus the final map programmmed at the end of S4[1.]

Case	*Strategy*	*S2*	*S3*	*S4*	*End S4*
1	HiRes	Gold 3	Ivory 1	Gold 1	Gold 1#1
2	HiRes	Ivory 1	Ivory 1	Gold 3	Gold 3#1
3	HiRes	Gold 2	Gold 2	Ivory 2	Ivory 2#1
4	HiRes 120	Ivory 1	Ivory 2	Ivory 2#1	Ivory 2#2
5	HiRes 120	Silver 3	Gold 1	Ivory 1	Ivory 1#1
6	HiRes 120	Gold 1	Gold 1	Gold 1	Gold 1
7	HiRes 120	Gold 3	Ivory 1#1	Ivory 2#1	Ivory 2#2
8	HiRes 120	Gold 3	Gold 3#1	Gold 1#1	Gold 1#2

[1]#1 and #2 denote modifications implemented by FOX following consideration of outcome measures.

Table 3 shows the progression of maps that was in use by each subject at the start of fitting sessions 2, 3, and 4, plus the final map at the end of session S4. Even by the start of session S2 chosen maps were already at an advanced stage, ranging from Silver 3 to Ivory 1. Over the remaining sessions there was an overall gradual progression, though several subjects did not change much between S2 and S4. Subjects 1 and 2 initially set themselves automaps that turned out to be slightly too high and later dropped back slightly by the last session. The syntax 'Ivory 2#1' denotes automap Ivory 2 which has been modified through one iteration of FOX using outcome measures.

Modifications at session S2

Following impedance telemetry and free-field audiometry, FOX deactivated electrodes 15 and 16 (the most basal) in two subjects (7 and 8) who showed poor thresholds at 6000 and 8000 Hz. Figure 1 shows the audiograms obtained before and after electrode deactivation in these subjects. All other subjects had satisfactory thresholds across the frequency range examined. In this group of subjects no electrodes were deactivated due to non-auditory stimulation.

Modifications at session S3

All initial audiometric thresholds were judged satisfactory, with median thresholds of 21 dB HL (range 13–28 dB HL). Group results are shown in Figure 2.

A§E phoneme discrimination was also good in all cases. Four subjects discriminated 19 out of 20 contrasts, and the other four 20 out of 20. FOX did not suggest any map modifications as a result but modified the pulse width in one case to avoid possible compliance problems based on the measured impedances. The results of A§E loudness scaling and speech audiometry are shown in Figures 3 and 4 respectively.

Modifications at session S4

Table 4 summarizes the modifications and final outcomes of the 4th session for the eight subjects. For each subject, the outcome measures are shown that prompted FOX to make modifications, as well as the re-measured outcome measures after the modifications. For example, subject 4 had a score of 0.9 on the loudness scaling at 250 Hz, which became 0.8 after the modification. The columns on the right list the parameters modified by FOX as well as the final outcome. For example, FOX changed the T-levels, the M-levels, and the gains in subject 4 and the final outcome of session 4 was 'optimal', meaning that FOX had no further recommendations. 'POR' denotes 'pending outcome requests', meaning that FOX still had recommendations for further map changes which would be addressed at the next follow-up session.

Subject 2 had manual deactivation of apical electrodes in an attempt to improve loudness scaling at 250 Hz. Based on a 40 dB HL threshold at 2000 Hz, FOX recommended the deactivation of electrodes 9, 10, and 11 (with frequency bands centred at 1387 Hz, 1648 Hz, and 1958 Hz respectively) in subject 5. The audiologist decided to only deactivate electrode 11 and to change strategy on this occasion, which resulted in a threshold of 20 dB HL.

This subject was using the HiRes120 strategy, where two adjacent electrodes are always stimulated simultaneously (in order to achieve current steering). Inactivating one electrode would cause a gap in the array sequence since current steering by means of two non-adjacent electrodes (the electrode before and the one after the inactivated electrode) was not possible by the fitting software. To avoid possible problems related to this, FOX therefore also changed from HiRes120 to HiRes strategy. The HiRes strategy is a monopolar strategy where only one electrode is stimulated at the time. Inactivating an electrode causes a physical gap in the stimulation pattern, which is intentional, but it does not jeopardize the strategy as such.

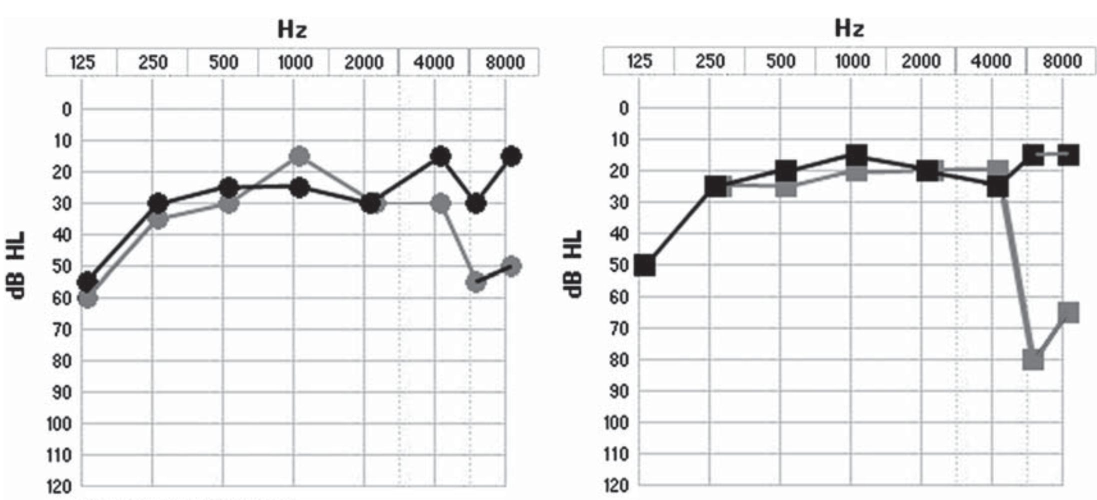

Figure 1. Audiograms of Subjects 7 and 8 at Session 2, thresholds before (light) and after (dark) inactivation of electrodes 15 and 16 by FOX.

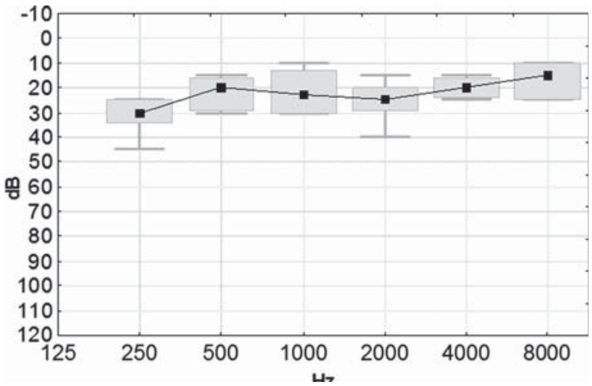

Figure 2. Free-field thresholds obtained for the group at the start of session S3. Central points indicate the median values, boxes the 25th and 75th percentiles, and whiskers the limits.

Discussion

This report outlines the fitting protocol that we typically follow for postlingually deafened adult CI recipients using the FOX system running the Eargroup's advice. This approach has several key features. Firstly, the switch-on session uses an automap generated by FOX, so that the majority of the session is spent counselling the subject rather than focusing on technical programming. We explain to the subject that we only expect him to hear a comfortable auditory percept initially, and that optimization will follow at subsequent sessions. This tends to reduce possible anxiety relating to the belief that sound clarity is dependent on the subject's psychophysical responses. It also postpones the 'fine tuning' of a program to a time when the subject has already habituated to the electrical signal. Secondly, we send the subject home from the first fitting session with two processors containing a total of six incremental automaps. This enables him to gradually increase stimulation levels over the ensuing two weeks, and often we find the subjects do not require much current increase after this period (see Table 3). Thirdly, we find the timing of four sessions in the first six months to be adequate to optimize the subjects' maps in the great majority of cases. Across these four sessions the total time spent is of the order of 2.5 hours, which includes all 'audiological' issues, i.e. technical explanations, device programming and performance measures. To the best of our knowledge, no publications exist reporting the time which is usually spent at fitting according to other procedures. However, it is our impression that our reported 2.5 hours in the first six months compare favourably with fitting times reported by traditional methods. Finally, the programming is outcome-driven where outcome is defined as psychoacoustical performance at the level of detection (audiogram), discrimination (A§E phoneme discrimination) and identification (A§E loudness scaling and speech audiogram).

The series of automaps is based on maps that have been proven to yield good outcomes ('green maps') in children and adults who were able to undergo all the tests. One consequence of this is that these automaps will change over time with the growing number of such green maps. Another consequence is that they can also be used in young children who are not yet able to undergo the psychoacoustical tests. The statistical approach used to generate these maps and their systematic use in all new CI-users provides confidence that they may also be suitable for the young child. With young children, the audiologist obviously needs to provide careful guidance to the parents as to how often the incremental maps should be changed and which signs of possible discomfort or intolerance to look for. It is our experience that the individual course is not significantly different in our paediatric subjects compared to our adult subjects.

In the set of subjects reported here the free field audiometry results were satisfactory in the majority of cases, without the need for any modifications. This is to be expected, as audiometric thresholds are chiefly dependant on processor parameters, rather than subject-specific factors (Boyd, 2006). However, the examples shown in Figure 1 demonstrate that FOX1.1$^{(EG0910)}$ was able to improve abnormally poor high frequency thresholds by deactivating basal electrodes. Without electrode-specific psychophysical measures it is not possible to state whether the electrodes involved were defective, were associated with high electrical thresholds, or were, perhaps, outside the cochlea. In the case of electrodes with high electrical thresholds one could argue that alternative parameter adjustments, such as increase in M levels and/or pulse width, could make an electrode useable without the need for deactivation. However, this can have a negative impact on the loudness scaling and can often only be done at the expense of a decreased pulse rate, and often auditory percepts are less clear from electrodes that have significantly different electrical dynamic range characteristics than other electrodes along the array. Deactivation of electrodes also changes other parameters, such as bandpass filter boundaries, and it can be a complex task to weigh up the relative advantages and disadvantages of electrode de-activation. FOX is able to take these considerations into account through reference to large numbers of existing subject maps and outcomes, and is able to verify recommendations immediately through repetition of the outcome measure that initiated the recommendation. In this

Table 4. Outcome measures resulting in modifications to maps during the final fitting session S4[1].

Case	*Audio*	*Speech*	*LS 250*	*LS 1000*	*LS 4000*	*Map modifications*	*Final result*
1					1.3 > 0.4	T, gain	Optimal
2			−1.8			Manual inactivation of apical electrodes	POR LS 250
3		Roll-over > no roll-over	0.7 > 0.6			M, gain, pulse width	Optimal
4			0.9 > 0.8		1.0 > 0.8	T, M, gain	Optimal
5	2000 Hz: 40 > 20 dB		−1.0 > −0.8		1.9 > 1.6	T, M, gain drop electrodes and change to HiRes	POR LS 4000
6							Optimal
7					1.1 > 1.1		POR LS 4000
8					1.4 > 1.3		POR LS 4000

context it is relevant to consider that the use of FOX in such a decision-making process can be particularly beneficial when the audiologist is relatively inexperienced in CI programming.

The A§E phoneme discrimination module is one of the key tools in the function of FOX as it reflects the spectral discrimination abilities of the cochlea, which is the level at which programming changes are effective, rather than at higher levels of the auditory pathways that are important for speech discrimination and language processing. In the cases reported here, A§E phoneme discrimination was perfect in all subjects by the end of session 4, and in most cases did not require any programming modifications. This is an illustration of the ceiling effect that is often encountered with this test. Although the results are always less than perfect prior to implantation, even with well-fitted hearing aids (this is one of our selection criteria), they usually become 'normal' very soon after implantation. This test contributed to the fine tuning of the device in only the minority of cases, but identification of poor phoneme discrimination is considered vital, and testing the 20 contrasts in an adult subject typically takes only 10–15 minutes, so does not increase the clinical workload significantly.

Based on this and our previous experience, we feel that A§E phoneme discrimination needs only to be assessed once in most cases, probably fairly soon after device activation (e.g. during the 3rd session). Adopting such a scheme would mean that during the first six months after surgery, no more than 2–2.5 hours need to be spent for each subject, spread over four sessions.

A§E loudness scaling showed slightly abnormal loudness ratings at 250 Hz (too soft) and 4000 Hz (too loud) in several subjects at session 3 (Figure 3). We presume that this can be explained by the fact that all were used to the sound of hearing aids and that it takes more time to accommodate to the new perception. There was a marked interindividual variation at 250 Hz. The four subjects with unaided thresholds of worse than 100 dB prior to implantation (Subjects 1, 2, 5, and 6), were the ones who scored the 250 Hz sounds as softer than the other subjects. These were the ones who were used to the strongest amplification with hearing aids. In session 4, FOX1.1*(EG0910)* recommended modifications to reduce the 4000 Hz loudness percept in five cases, but this was only partially successful, resulting in pending outcome requests (LS 4000) at the end of session 4 in three of the subjects. On the other hand, FOX1.1*(EG0910)* improved the loudness scaling at 250 Hz in four subjects and was successful

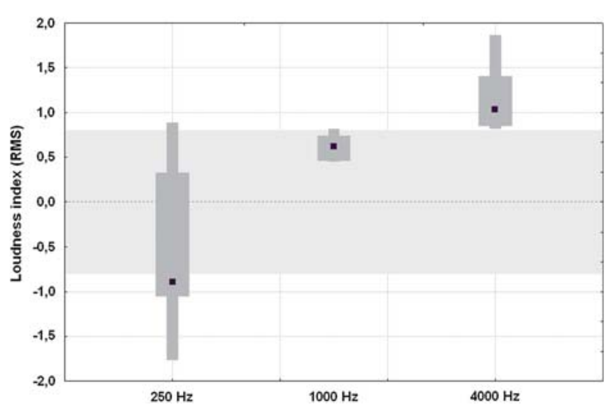

Figure 3. Loudness scaling results for the group at session S3 for 250, 1000, and 4000 Hz. Central points indicate the median values, boxes the 25th and 75th percentiles, and whiskers indicate the limits. The gray zone indicated the 95% confidence interval in hearing subjects.

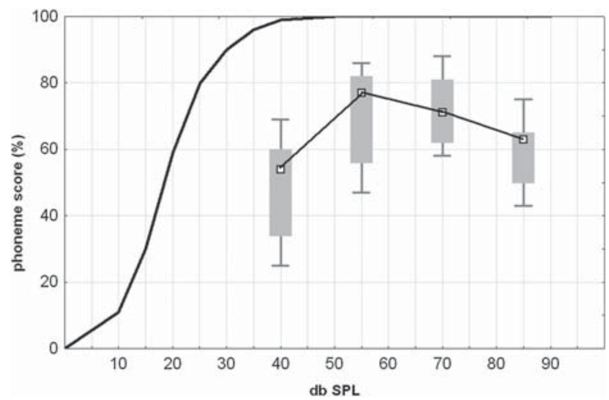

Figure 4. Speech audiometry group results for the session S3. Central points indicate the median values, boxes the 25th and 75th percentiles and whiskers indicate the limits. The solid curve represents the median of scores from normally-hearing individuals.

in three of these. The remaining subject could not be retested due to unavailability relating to a separate severe medical condition. She reported a distorted sound percept when narrow band noise of 250 Hz was presented. The audiologist decided to deactivate the most apical electrode manually which corrected the distorted percept and LS 250 remained as a POR for checking at the next session.

Speech audiometry can be important, particularly in order to identify excessive roll-over at high intensities. Some roll-over is inevitable as the highest intensity speech components are subject to output limitation inherent in the processor function, but often roll-over can be increased due to subject-specific factors such as electrode compliance limits or abnormal loudness growth. Subject 3 showed a high degree of roll-over (Figure 5), which was successfully corrected by FOX1.1(EG0910) through modifications to M levels, gain, and pulse width (Table 4).

FOX is able to manipulate more variables than those routinely modified by most audiologists, including T-levels, M-levels, gains, pulse width, filter boundaries, the activation state of electrodes, and even changing the stimulation strategy. Many of these parameters interact with each other, such that efficient programming requires a comprehensive understanding of these issues by the audiologist. In four out of the eight subjects reported in this study the fitting, based on the outcome results at the end of session 4, was considered 'optimal' by FOX1.1*(EG0910)*. The other four cases had only minor remaining issues, relating to loudness scaling at a single frequency, resulting in new map modifications with pending outcome requests that would be addressed at the next fitting session.

While FOX is able to efficiently manage most aspect of programming, it is perhaps worthwhile pointing out that an experienced audiologist is still an important component of the fitting process. Reliable outcome measures are critical for optimal use of FOX and the role of the audiologist here should not be underestimated. There are also some programming issues that FOX is less able to assess accurately, such as non-auditory stimulation, and there may be subject-specific factors relating to lifestyle (music appreciation, for example) which might impact on programming preferences. When FOX makes recommendations for programming parameter changes these may be accepted or rejected by the audiologist and such decisions require good understanding of the fitting process. In this way, FOX becomes a useful tool for the experienced audiologist in the fitting process.

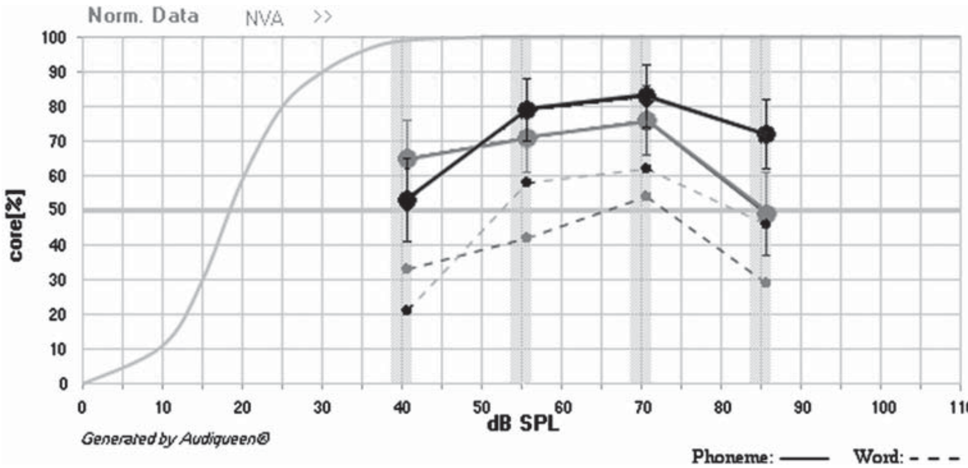

Figure 5. Speech audiometry for Subject 3, before (light symbols) and after (dark symbols) modification of M levels, gain, and pulse width by FOX. Solid lines indicate phoneme scores and dashed lines indicate word scores.

On the other hand, FOX might be expected to be especially useful when an experienced audiologist is not available. From anecdotal experience, grossly inappropriate maps are occasionally encountered that have been generated by inexperienced audiologists, a situation which would never occur if FOX is used as an assistant for programming. A key aim of FOX, therefore, is to provide a systematic approach to programming which can standardize fitting across different centres.

Thus, our initial fitting protocol, using the FOX1.1*(EG0910)* software application, is fundamentally different from traditional methods in that it starts 'blindly' with preprogrammed processors. This is a 'one size fits all' approach at the start with the 'tailoring' of the program to the individual subject at a later stage. It may seem weird to use a 'one fits all' approach with preset maps coming from other CI-users. However, previous studies using principal-components analysis (PCA) showed that both the profiles of ECAP thresholds and the conventional T and C levels across the full electrode array are governed by two factors, the major being the overall level (termed shift), and accounting for 90% of the variance (Smoorenburg et al, 2002). Our switch-on approach incorporates this factor by offering an incremental series of automaps taking care of this shift-effect. The tailoring to the individual profile of the CI-user can be based on electrophysiological measures (like ECAP thresholds), but as outlined in the introduction, these ECAP thresholds only weakly correlate to the behaviourally obtained map-levels. Our tailoring is done with a strong emphasis on outcome measurements. At this stage all recipients have access to the same series of start-up automaps, so the only individual variability lies in the level ultimately tolerated. Future automaps may be different for different subgroups of CI-users depending on factors still to be defined, such as age at implantation, duration or cause of deafness, etc. This report demonstrates that good results can already be obtained with a relatively small clinical workload and that a systematic approach, with the assistance of an intelligent agent like FOX, is capable of selectively improving test results. It is likely that further improvements can be expected with increasing experience and data analysis.

It can be argued that huge differences exist in CI-programming strategy between different centres and even between different audiologists from one single centre and that all strategies seem to yield equally good results. However it is our feeling that hardly any outcome is ever measured or presented. Most papers report on correlations between map-levels based on ECAP-measures to those obtained behaviourally (e.g. Willeboer & Smoorenburg, 2006; Abbas et al, 2006). If psycho-acoustic outcome is presented, this is almost always word or phoneme scores on speech lists presented at one or two presentation levels (typically 60–70 dB SPL). These results depend not only on the cochlear functioning but also on the central processing of the signals and as a consequence on the cognitive functioning of the CI-user, the duration of deafness and many other factors. The inter-individual variability is very high which makes it statistically almost impossible to demonstrate differences between different programming strategies. For an individual patient, we believe that it is justified to try to optimize the detection threshold and the coding of loudness and spectral content by modifying the fitting parameters, and we speculate that this results in better speech understanding ultimately.

To date, the set of rules we have worked with are derived from mapping data and outcomes recorded in our centre, i.e. the 'Eargroup advice'. FOX is keeping track of all the MAP data with their corresponding outcome and also of the changes made and the measured effects of these changes. This growing database is now analysed on a regular basis and if possible, the rules are modified to further optimize the advice. Future developments will include automating this analysis and rule optimization such that FOX will include a self-learning engine. As outlined above, the Eargroup's advice targets the optimization of psychoacoustical outcomes. FOX, however, should not be associated solely with the Eargroup's advice. It should be emphasized that other experienced groups are able to develop their own 'set of advice rules' which can use the same or other outcomes. It is perfectly conceivable that other outcomes may be used, such as electrophysiological test results or even subjective questionnaires. FOX incorporates a user-friendly interface which allows the input of additional rules by professionals without the need for knowledge of programming languages. There may be several advantages for audiologists to become involved in this process, as (1) it encourages the expert to critically analyse his way of working and turn it into a systematic set of rules, (2) it makes the individual's expertise available to peers, and (3) it systematizes the fitting procedures, making it more easy to share skills with others and to provide a standardized procedural approach.

Conclusion

It is concluded that the introduction of the intelligent agent FOX in the programming of cochlear implants is feasible and yields good results as measured by means of psycho-acoustic tests. It represents the introduction of artificial intelligence in this domain. It is anticipated that this will systematize CI programming, reduce the fitting time, and optimize the results. Future developments include multicentre trials with FOX, further improvements of the Eargroup's set of rules, the introduction of other outcome measures, the creation of rules that address even more electrical parameters, and the development of other sets of rules reflecting the procedures used by other experts in the field. The incorporation of a self-learning engine will allow a continuous improvement of the rules based on the experience in real CI-users.

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