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Development of a Software Tool Using Deterministic Logic for the Optimization of Cochlear Implant Processor Programming

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An intelligent agent, Fitting to Outcomes eXpert, was developed to optimize and automate Cochlear implant (CI) programming. The current article describes the rationale, development, and features of this tool.

Background: Cochlear implant fitting is a time-consuming procedure to define the value of a subset of the available electric parameters based primarily on behavioral responses. It is comfort-driven with high intraindividual and interindividual variability both with respect to the patient and to the clinician. Its validity in terms of process control can be questioned. Good clinical practice would require an outcome-driven approach. An intelligent agent may help solve the complexity of addressing more electric parameters based on a range of outcome measures.

Methods: A software application was developed that consists of deterministic rules that analyze the map settings in the processor together with psychoacoustic test results (audiogram, A§E phoneme discrimination, A§E loudness scaling, speech audiogram) obtained with that map. The rules were based on the daily clinical practice and the expertise of the CI programmers. The data transfer to and from this agent is either manual or through seamless digital communication with the CI fitting database and the psychoacoustic test suite. It recommends and executes modifications to the map settings to improve the outcome.

Results: Fitting to Outcomes eXpert is an operational intelligent agent, the principles of which are described. Its development and modes of operation are outlined, and a case example is given. Fitting to Outcomes eXpert is in use for more than a year now and seems to be capable to improve the measured outcome.

Conclusion: It is argued that this novel tool allows a systematic approach focusing on outcome, reducing the fitting time, and improving the quality of fitting. It introduces principles of artificial intelligence in the process of CI fitting. **Key Words:** Artificial intelligence—Cochlear implant—Deterministic logic—Fitting—Intelligent agent—Optimization—Outcome—Programming—Psychoacoustics.

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Cochlear implantation is now widely accepted as an effective treatment for profound deafness (1,2). Several commercial devices are currently available, but all share many common features such as the basic combination of an externally worn sound processor that delivers power and coded signal to an implanted receiver package via a transcutaneous radio frequency transmission link, which in turn delivers a sequence of electric pulses to an array of electrodes surgically placed into the scala tympani of the cochlea. There are also considerable similarities between the various coding strategies used in different devices, which define the pattern of electric pulses delivered to the cochlea in response to acoustic input to the processor.

After surgical implantation, the external sound processor must be appropriately programmed and customized for the individual. The aim of this is to set a number of electric parameters to ensure that the electric pattern generated by the internal device in response to sound stimulation yields an optimal auditory percept (3). The definition of this optimum is not unequivocally defined, a problem that is further addressed in the discussion. Several electric parameters are available, and all their values together are commonly called the MAP. Finding and programming the optimal values for an individual

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are commonly called the act of fitting. It is achieved using proprietary software and a hardware interface connected to the processor and depends on behavioral responses from the Cochlear implant (CI) user.

From the early years onward, many electric parameters have been set at default values that are mostly left untouched during the fitting process. Fitting is usually restricted to setting the threshold of audibility for electric stimulation, plus dynamic range, for each electrode separately. Both levels may vary considerably among individuals and among different electrodes along the array within individuals. For this reason, the initial task is for the audiologist to measure the threshold and some measure of upper loudness tolerance (such as "most comfortable level") for each electrode to define a range of outputs that provides a comfortable percept when the resultant MAP is activated.

After the initial "fitting" and activation of the processor, several review sessions are normally required to remeasure these levels to accommodate the increase in dynamic range that typically occurs as the user becomes accustomed to the electric stimulation over the first few months of device use (4). The need for follow-up sessions is particularly important for young children because it is generally very difficult to assess sensitivity to electric stimulation in this population due to their cognitive status and lack of experience of auditory sensations. After stabilization of electric dynamic range (EDR), fitting sessions are usually limited to periodical checks, typically annually, as long as progress remains satisfactory.

Although threshold and upper loudness levels are the main parameters commonly used for the generation of an appropriate MAP, there are many others that can be adjusted within the fitting software. The most common additional adjustment is the deactivation of individual electrodes if deemed necessary, usually if they show high thresholds, small dynamic ranges, or produce non-auditory stimulation. Although clinicians may adjust a number of other program parameters, time constraints, limited assessment procedures, and the unavailability of certain parameters in commercially available fitting software make it impractical to do so on a routine basis. Optional parameters include bandpass filter boundaries, gain, microphone sensitivity, output compressive function, interpulse interval, stimulation rate, and so on. Our observation of clinicians throughout Europe has taught us that clinicians often leave most of these parameters unchanged from their default settings.

It is important to notice that the main criterion used is the patient's behavioral response. This reflects detection at low intensities to set the lower stimulation level and some appreciation of comfort, maximal comfort, or discomfort to set the upper level.

Once behavioral fitting parameters are stable, it is usually assumed that the MAP is optimally adjusted. Occasionally, the user may complain regarding the subjective quality or tone of the auditory percept. If a user is performing at a lower level than might be expected, then fitting measures may be repeated, but if these seem reliable, then it will be accepted that performance is probably optimal for that particular user because it is well known that outcomes vary considerably even within a relatively homogeneous group of CI users (5). In our experience with a number of CI centers, MAP adjustments are not often based on formal outcome measures, although this may be different for different CI centers. Even when measured outcome is used, this is rarely fed back into a validated and systematic way to change the MAP. One of the consequences is that the same outcome may result in significantly different MAP changes when given to different clinicians.

Repeated fitting sessions, even when they merely address the limited number of electric parameters described earlier, are very time-consuming for a CI center, and there is therefore a perceived need to make this process as efficient as possible. However, apart from time considerations, the efficiency of the process is clearly also affected by how much benefit is gained by very accurate processor fitting. There exists a school of thought that the central auditory system is able to accommodate to a fairly wide range of inputs from the cochlea such that as long as speech sounds are audible, then the language processing centers of the auditory system can satisfactorily adapt through neural plasticity. To this end, several studies have shown that processor fittings can be simplified to a certain degree without significant detriment (6–8).

Although this line of thinking may have useful implications for certain clinical situations, it is commonly believed that accurately adjusted processor MAPs do generally result in better outcomes in terms of speech understanding (9,10). The practical question, however, is how to achieve this without spending excessive amounts of clinical time. Indeed, if one considers 5 independent mapping parameters with only 5 critical values possible for each, this would yield $5^5 = 3{,}125$ possible combinations. These are more than the patient or clinician could reasonably evaluate by traditional methods.

Several ways to reduce the fitting time have been developed over the years. They can be summarized by 2 strategies: 1) to introduce objective measures that serve to predict the optimal MAP values and 2) to set MAP values on a group of electrodes rather than on individual electrodes.

Objective measures are often performed during surgery, although they can also be performed at any moment after surgery. They include measurements of the electrically evoked compound action potential (eCAP) using back-telemetry (11), electrically evoked auditory brainstem recordings (12), and electrically evoked stapedius reflex thresholds (13). These have been shown to identify stimulation levels within the behavioral dynamic range, but show considerable variability and do not accurately indicate the limits (threshold and maximum comfortable loudness) of the dynamic range (14,15). They are mainly used as a starting point for user MAPs, where behavioral measures are still important to fine-tune the processor fitting. Much work has been performed to optimize the correlation between these objective measures and their behavioral equivalents, with most effort in recent years directed toward eCAP measures with the hope that they might satisfactorily be used as a means of "automated" fitting, dispensing with the need for behavioral measures altogether (16).

Changing the MAP values for a group of electrodes is facilitated in the fitting software of the different devices. For instance, several electrodes can be selected together, and their MAP values can be modified groupwise. Shift and tilt functions allow changing the profile of the lower or upper stimulation levels of the entire electrode array (17), a group of values can be changed by interpolation, etc.

A limitation of traditional processor fitting is that it depends on the experience and knowledge of the audiologists or other personnel performing the measurements and adjustments. Behavioral responses, especially when obtained from patients with no or little auditory experience, may vary according to the methodology used, instructions to the patient, and so on. Training in fitting is usually provided primarily by the CI manufacturers, but there exists no standardized methodology, which makes it difficult to verify the quality of this aspect of the fitting process. Anecdotal reports from clinical specialists working with CI manufacturers suggest that patients with grossly inappropriate MAPs are occasionally encountered even in centers where the usual amount of training has been provided. One can argue that after more than 20 years of cochlear implantation, the act of fitting is still a matter of craftsmanship where much time is invested to set merely a partial number of the electric parameters based on behavioral responses relating to a level of detection and some level of comfort and of which the reliability can be questioned.

One of the basic tenets of the system developed here is that it is the cochlea that is the main site of dysfunction in the typical CI user. Therefore, no matter to what extent the central auditory system is able to "compensate" for an imperfect signal from the (implanted) cochlea, it will inevitably be able to function better if the sound coding by the (implanted) cochlea can itself be optimized. Furthermore, the implanted cochlea is clearly the level of the auditory system to which we have the most direct access during CI programming.

Outcome measures that reflect cochlear function are limited, at least in terms of tests that can be readily performed in a routine clinical setting. Audiometry can assess detection, but speech recognition testing involves higher-level linguistic processing and so only indirectly relates to cochlear function.

Largely to address this problem, we developed a test battery known as the *Auditory Speech Sounds Evaluation* or A§E (18,19; *http://www.youtube.com/watch?v=svlEsF73CAA*). This is a psychoacoustic test suite attempting to assess these cochlear functions in more detail. The core module is a discrimination test based around 20 pairs of speech sounds, which are presented in an oddity paradigm and which can provide a clinical indication of the frequency-resolving power of the cochlea. More recently, we have added a loudness scaling module that indicates loudness growth at 250 Hz, 1, and 4 kHz and several modules assessing the coding of temporal fine structure in isolated and linguistic contexts.

To date, audiometry, A§E phoneme discrimination (20 phoneme pairs), A§E loudness scaling (with narrow band noise centered at 250, 1,000, and 4,000 Hz), and speech audiometry (open set monosyllables presented at 40, 55, 70, and 85 dB SPL) are routinely used in our center to measure the quality of the fitting. Strategies have been developed to feedback this information to MAP changes to improve the measured outcome. This approach, however, has faced us with the complex relationships, correlations, and interdependencies between the many electrical and psychoacoustic variables. For any professional, even the very experienced one, it becomes difficult to master all these functional relationships. For that matter, we have made a first attempt to introduce artificial intelligence (AI) in this process.

Artificial intelligence is a relatively new science with many theoretical applications, one of which is the making of rational decisions to maximize outcome in complex systems. It not only attempts to understand but also to build intelligent entities (20). An intelligent agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators. For our purpose, the psychoacoustic tests serve as sensors and the MAP (together with the fitting software) as actuator. Internally, the agent function is implemented by an agent program. It is beyond the scope of the present article to elaborate in detail on AI. Briefly, the program is based on knowledge, logic, and learning skills. The core consists of logic, which can be either deterministic or nondeterministic (also called stochastic or probabilistic). Deterministic logic is typically rule-based. Typical forms of nondeterministic logic are neural networks, genetic algorithms, etc. A comprehensive description of state of the art of AI can be found in Russel and Norvig (21).

During the past 10 years, we have been developing an intelligent software system or intelligent agent that is designed to optimize CI processor MAPs. In its actual state, it uses the psychoacoustic outcome measures mentioned earlier, although it is conceived to handle other measures such as electrophysiologic test results or questionnaires as well. It analyzes the actual MAP settings together with the outcome obtained with it. Its primary aim is then to provide recommendations for mapping adjustments to optimize the electric signal presented to the cochlea without the need for conventional behavioural fitting measures, which are subject to the limitations previously outlined.

This software tool is termed the "Fitting to Outcomes eXpert" or FOX. The aim of this report is to outline the principles behind its development, describe its main features, and to demonstrate its function through some case samples.

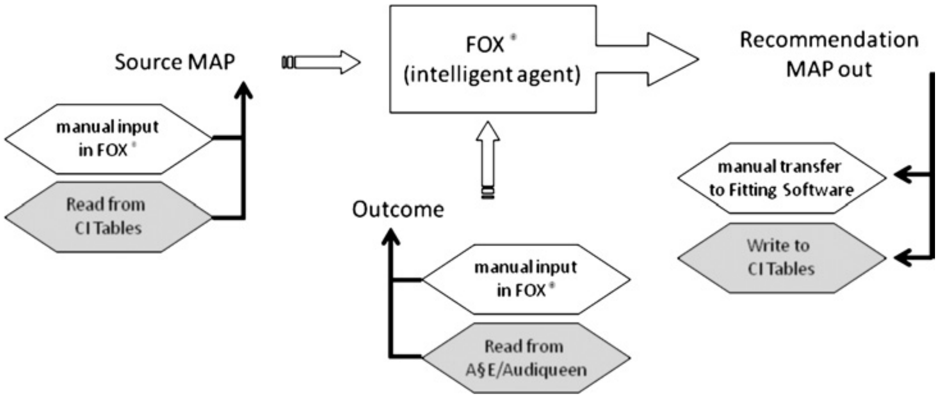

FIG. 1. Fitting to Outcomes eXpert working principle. An initial program and various psychoacoustic test results may be input into FOX, which then delivers fitting recommendations as output. *Shaded boxes* illustrate function when interfaced with proprietary outcome and CI fitting software, whereas *unfilled boxes* denote stand-alone function.

Principles Behind the Development of FOX

Fitting to Outcomes eXpert (registered with interdeposit digital number BE.010.0112303.000.R.P.2008.035.31230) is based on a set of programming rules that have been established from analysis of clinical MAPs and outcomes over several years' experience with more than 600 CI users at our center. The system, which is written using .net technology, currently contains a large number of determinist "rules" that link a range of outcome measures to the most important parameters that can be adjusted within the CI fitting software. This particular set of rules constitutes the Eargroup "advice," but additional "advices" can be developed and added to FOX from other sources (e.g. other clinical experts, CI manufacturers, etc.), and a user-friendly interface allows the input of additional rules by professionals without the need for knowledge of programming languages. Separate advices (each made up of a set of rules) are available for different situations such as different CI devices, types of processor, or the type of fitting session because any particular rule may operate differently under different situations.

Fitting to Outcomes eXpert can be used as a stand-alone software package but is also able to interface directly with proprietary outcome data sources and CI fitting software through direct synchronization. In this report, we demonstrate how it operates together with the SoundWave fitting system from Advanced Bionics, but it can potentially interface with fitting software from other CI manufacturers. Fitting to Outcomes eXpert works as an iterative process and can be run several times. The basic mode of operation is illustrated in Figure 1, which shows options for independent function and when interfaced with the Soundwave software ("CI tables") and the Audiqueen database containing outcome data. Thus, FOX takes an existing CI MAP and analyzes the outcome data associated with that MAP. Using deterministic logic based on its set of rules, it then recommends changes to the CI MAP that are expected to improve outcomes. After these changes, outcome measures can be repeated and fed back to FOX, which may suggest further changes or confirm an optimal fitting.

Table 1 illustrates the operation of a typical rule. The top row shows the outcome condition that elicits the execution of the rule. In this case, it translates as: "IF the listener fails to discriminate the contrasts /z – s/ or /a – r/ of the A§E phoneme discrimination, THEN execute the rule". The left column shows the breakdown of the possible effects of the rule based on additional criteria that consider the actual MAP settings. In this case, the first additional criterion (Rule 4d7 186) reads "IF the average M level of the electrodes coding the acoustic frequencies between 0 and 600 Hz is lower than 330 clinical units (CU), THEN execute what follows." The right column shows the effect produced by the execution of the rule. In this case, the first effect reads "increase the dynamic range of the electrodes coding the frequencies 0–600 Hz by 20% if both contrasts were not discriminated OR by 10% if only one contrast was not discriminated."

Outcome measures that may be input to FOX include the following:

- Acoustic (free field) thresholds from 250 Hz to 8 kHz;
- Loudness growth function for 250 Hz, 1, and 4 kHz;

TABLE 1. *Typical rule featuring in the Eargroup's advice*

[z − s] + [a − r] < 2		
Rule 4d7 186	map.Maximum_0_600 < 330	map.Maximum_0_600 = map.Minimum_0_600 + (map.Maximum_0_600 – map.Minimum_0_600) × (100 + (2 − [z − s] − [a − r]) × 10) / 100

See text for details.

- Auditory Speech Sound Evaluation discrimination of 20 phoneme contrasts at 70 dB HL (re. 1-kHz narrowband noise);
- Speech audiogram (scores at 40, 55, 70, and 85 dB SPL).

Additional outcome measures can potentially be incorporated into FOX, following development of appropriate rules. These could potentially include other behavioral test data, objective test data (eCAP measures, stapedius reflex thresholds, etc.), questionnaire data, or other performance measures.

Mapping parameters currently incorporated into FOX include the following:

- Electric thresholds (T levels) and upper loudness limits (M levels);
- Input dynamic range;
- Gain;
- Electrode activation/deactivation;
- Processing strategy (HiRes, HiRes 120, etc.);
- Pulse rate;
- Bandpass Filter boundaries;
- Automatic Gain Control;
- Sensitivity;
- Volume.

In the future, rules for additional parameters may be developed.

It should also be noted that a number of safety measures are available to control the risk of errors and of overstimulation. These provide warnings or constraints to the MAP settings or changes that are allowed, restricting the operating freedom within stricter and safer limits than those the manufacturer's fitting software allows. Some are based on clinical expertise and intuition. For example, increases in the maximal or most comfortable stimulation level (M level for AB devices) are restricted to 80 CU per iteration. Other safety measures are based on statistical analysis of all MAPs that have ever been given to CI users. For example, the distribution of all these settings is defined by an average value μ and a standard deviation (SD) for each MAP parameter. Whenever an advice attempts to modify the value of an electric parameter to beyond the interval $\mu \pm 2$ SD, this attempt is highlighted to alert the audiologist. Whenever an advice attempts to modify the value to beyond the interval $\mu \pm 5$ SD, FOX will block the modification, alert the audiologist, and provide the option to take over programming outside the control of FOX. For example, the highest M level that the current settings of FOX would accept are 393 CU for the AB HiRes90k device. These additional safety measures are particularly important when fitting is being performed by relatively inexperienced clinicians.

Features and Operation of the FOX System

Fitting to Outcomes eXpert is able to provide MAPs for the initial switch-on sessions based on demographic data, and this "automap" function is described in the succeeding sentences. In addition, the system can be used to optimize MAPs that have been originally generated from standard behavioral fitting sessions.

A user-friendly graphic interface presents a list of available MAPs for a given patient. These MAPs are available to FOX by means of synchronization between the proprietary fitting software and its own database. An individual MAP is selected and read into FOX.

A specific "advice" is then selected from a list, according to, for example, the particular CI device or type of fitting session (such as initial switch-on). Figure 2 shows the advice selection screen together with the list of outcomes that can be entered for that particular advice. The audiologist can enter whatever outcomes have been obtained from the patient using the MAP being analyzed. These test results can be entered manually or they can be imported seamlessly from the A§E test suite or an Audiqueen (Otoconsult, Belgium) export file. F2

Once data entry is complete, FOX analyses the MAP settings together with the outcome and formulates its feedback. The response from FOX is in 2 forms: messages and MAP changes. Figure 3 shows a screen shot of the software showing a typical FOX response. Outcome measures that were entered are listed in the left panel. The main panel contains several "messages," in this case highlighting that changes to the MAP are suggested, plus a prompt requesting additional outcome data. At the bottom of the screen are recommendations to adjust M levels for 6 electrodes and gains for 4 electrodes. These fitting parameter suggestions may be executed manually by the audiologist or automatically by direct communication with the fitting software upon the audiologist's approval. F3

Outcome measures using the modified MAP can then be made and entered into FOX such that more than 1

FIG. 2. The "advice" selection screen. In this case, it is a follow-up session with an Advanced Bionics device. On the *left* are listed the outcome measures that can be entered for this particular advice.

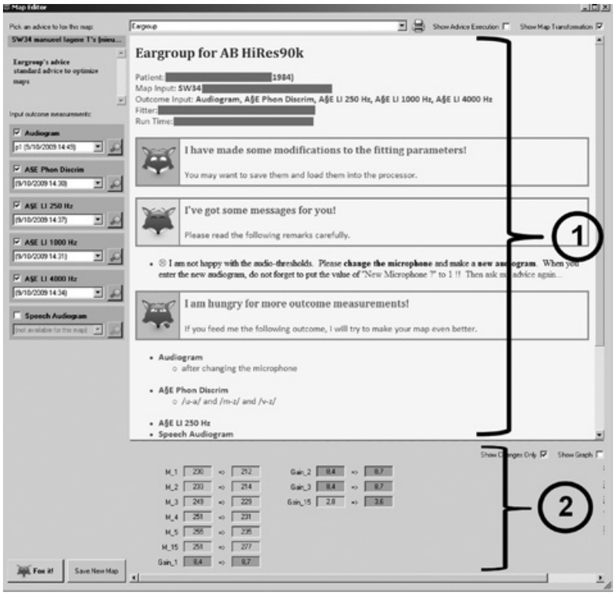

FIG. 3. A typical response from FOX, after input of outcome data, is illustrated in this screen shot. The output consists of messages (1) and suggested modifications of the MAP settings (2). See text for further details.

iteration may be performed at a fitting session, whereby FOX will assess the new outcome measures with reference to the new MAP and then possibly suggest further MAP changes. Alternatively, depending on the type of session or time after initial activation, the patient may be advised to use the new MAP until the next fitting session, when outcome measures may then be performed. If no programming changes are required after analysis by FOX, then an appropriate message is returned by the system.

The "Automap" Function

The current version of FOX contains an advice for the production of MAPs in the absence of any preexisting behavioral fitting measures or outcome measures. These "automaps" are generated based on a statistical analysis of all available MAPs from the CI population that yielded good outcomes (where FOX judged that no further attempts to improve the outcome could be made). They would typically be used at the initial switch-on session, when an incremental series of up to 10 automaps can be generated to accommodate early increase in dynamic range (loudness tolerance). This makes the initial fitting process more systematic and can save a lot of clinical time. As soon as the CI user has a level of acceptance to electric stimulation, and the first outcome measures are available, FOX can then be used to individualize and optimize these MAPs. The case sample in the succeeding sentences provides further details of the automap function.

In the future, we plan to develop rules so that FOX can generate automaps for specific subgroups of patients based on their medical history, age and duration of deafness, audiologic, and other data.

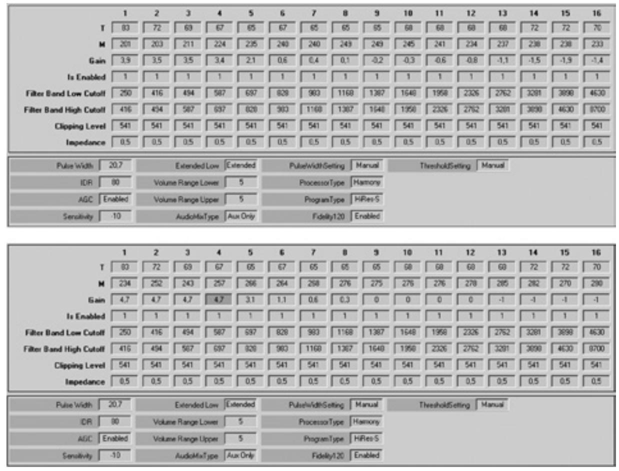

FIG. 4. MAPs at Sessions 2 (Gold 2, *top*) and 3 (Ivory 1, *bottom*).

Case Example

A 22-year-old lady requested a cochlear implant when she was about to finish university studies. She had been diagnosed with a 60-dB sensorineural hearing loss of unknown etiology at the age of 3. She received hearing aids immediately and entered mainstream education. Her hearing thresholds had further deteriorated to 90 dB HL by the age of 12.

Imaging suggested normal cochlear morphology, and surgery was uneventful. An Advanced Bionics HiRes90k device was implanted with full insertion of the electrode array, and first fitting took place 3 weeks later. A series of 10 automaps, with incrementally increasing stimulation levels, was created (from quietest to loudest; these are known as the switch-on automap; Silver 1, 2, and 3; Gold 1, 2, and 3; and Ivory 1, 2, and 3). The switch-on MAP was used for the duration of the switch-on session. At the end of this session, the silver MAPs were programmed in 1 speech processor and the gold MAPs in a second processor, and the patient received both processors to take home. She was instructed to start with the

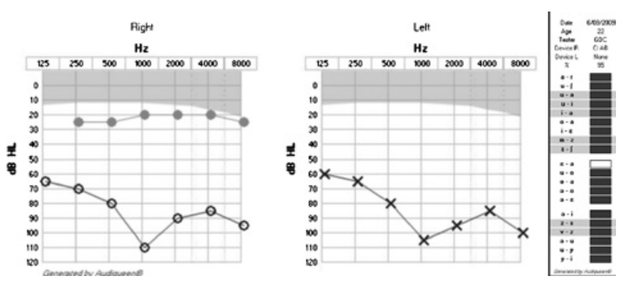

FIG. 5. Outcomes at Session 2. The audiogram (*left*) shows the unaided results with headphones before implantation (pure-tone average of 93 dB HL on both sides) and the results with the CI in free field after implantation (pure-tone average of 22 dB HL). The A§E discrimination (*right*) shows that 19 of the phoneme contrasts were well discriminated (*gray fields*), and that 1 contrast was not (*white field*).

MAP Silver 1 and to switch to an incrementally louder MAP every day as long as the sound percept remained tolerable.

The second session was 1 week after switch-on. The F4 patient had increased up to MAP Gold 2 (Fig. 4, top), and outcomes were measured using this MAP. According to the routine follow-up protocol in the Eargroup, audiometry and A§E phoneme discrimination were assessed, and the results are given in Figure 5. Both F5 the MAP settings and the outcomes were entered into

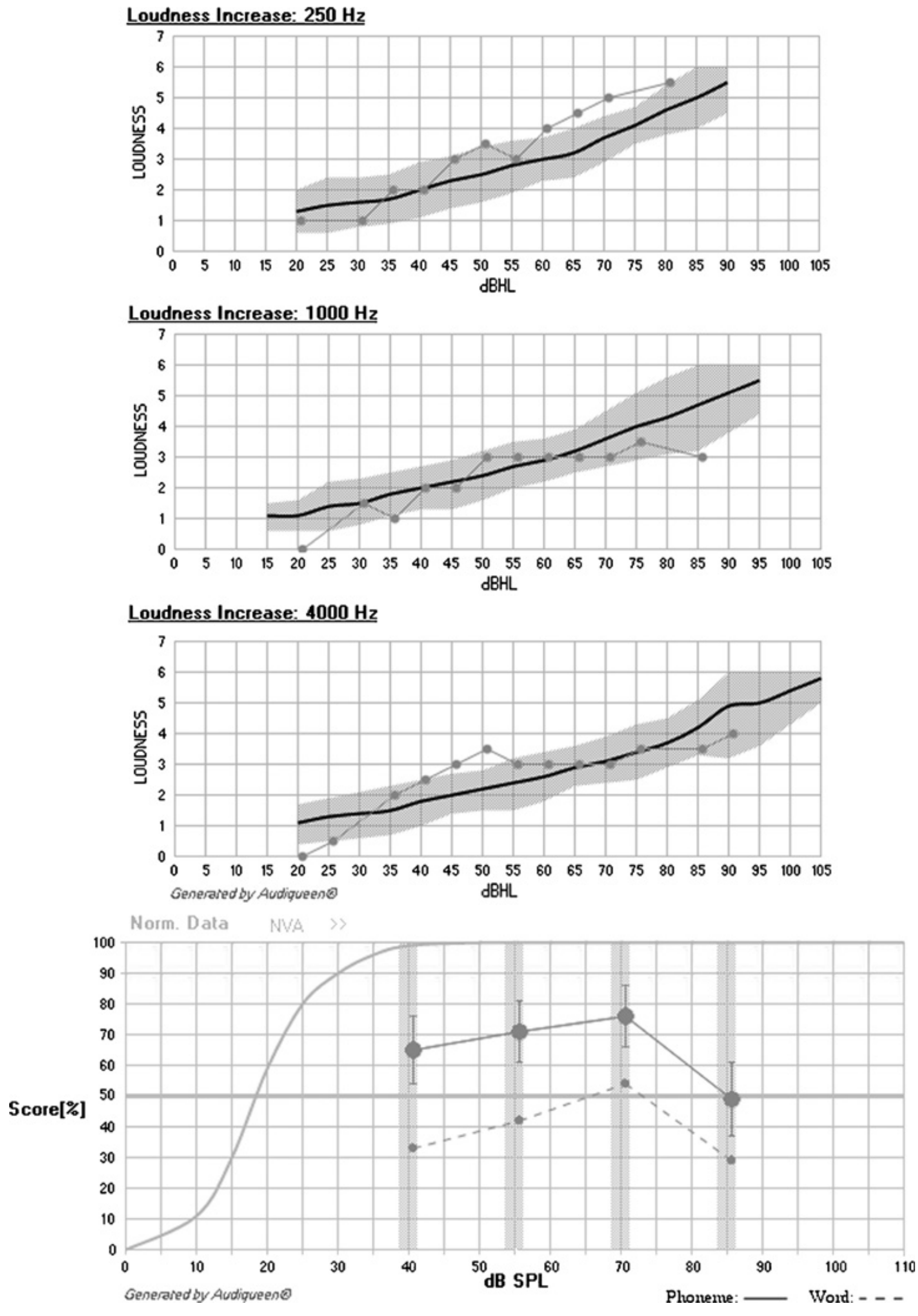

FIG. 6. Outcomes at Session 3. The loudness scaling at 250, 1,000, and 4,000 Hz are plotted (*dots connected by solid line*) on the top 3 graphs representing the perceived loudness on the vertical axis (ranging from 0 = inaudible to 6 = too loud) as a function of the presented intensity. The *thick black line* and the *gray zone* represent the average score and 95% confidence interval, respectively, in normal-hearing listeners. The speech audiogram (*bottom graph*) shows the phoneme and word scores of open-set monosyllable lists presented at 40, 55, 70, and 85 dB SPL.

FIG. 7. Fitting to Outcomes eXpert advice at Session 3. Fitting to Outcomes eXpert proposed some MAP changes and to repeat speech audiometry and A§E loudness scaling at 250 Hz.

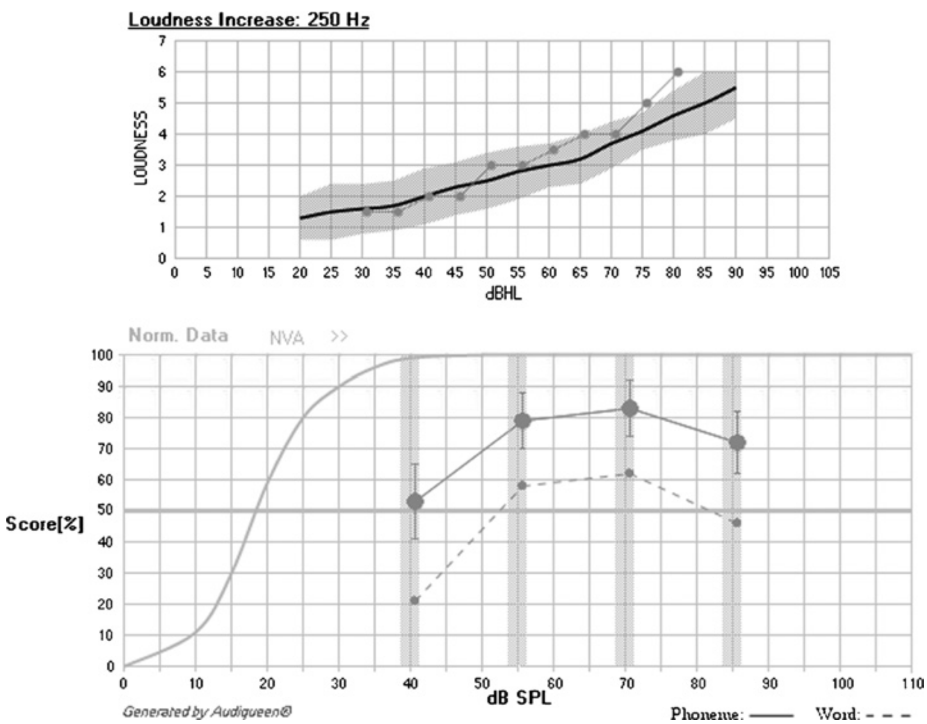

FIG. 8. Repeated outcomes at Session 3, after implementing the MAP changes proposed by FOX. The loudness scaling at 250 Hz shows values that are more within the normal zone than previously. Speech audiometry shows better scores at 55, 70, and 85 dB SPL and less rollover.

FIG. 9. Fitting to Outcomes eXpert response at Session 3 based on the repeated outcome measures.

FOX, which recommended leaving the MAP unchanged. The speech processor was loaded with MAP Gold 2 plus 2 higher automaps (Gold 3 and Ivory 1), and the patient was instructed to try the higher automaps occasionally to see whether they were comfortable.

The third postoperative session was scheduled for 2 months later, that is, 10 weeks after switch-on. At this time, the patient had moved up 2 more automap levels (to Ivory 1; Fig. 4, bottom), and outcomes were measured using this MAP. Auditory Speech Sounds Evaluation loudness scaling and speech audiometry (open-set consonant-vowel-consonant list at 40, 55, 70, and 85 dB F6 SPL) were assessed, and the results are given in Figure 6. Both the MAP settings and the outcomes were entered into FOX.

On this iteration, FOX proposed some MAP changes and to repeat speech audiometry and A§E loudness scal- F7 ing at 250 Hz (Fig. 7). It can be seen that loudness percepts at 250 Hz were louder than ideal, and that the speech audiometry shows some rollover at 85 dB SPL (Fig. 6). The suggested MAP changes were an overall slight decrease of the M level, an increase of the gain on 5 most basal electrodes, and a slight increase of the pulse F8 width. Figure 8 shows the repeated outcome measures after these were implemented.

A further iteration of FOX was then run using the new MAP parameters and the repeated outcome measures. On this occasion, FOX proposed a few minor MAP changes (further lower the M level and increase the gain on the 5 most basal electrodes) but did not request any new out- F9 come measures (Fig. 9). These changes were implemented, and the patient returned home.

DISCUSSION

The traditional approach to CI programming has remained essentially unchanged since the introduction of commercial devices some 20 years ago. Generally, the fitting process (as it is performed in usual clinical practice) can be considered to be "comfort driven," in that the primary goal is to provide electric stimulation within the dynamic range (from threshold up to most comfortable level). This applies to individual electrodes and to active MAPs when multiple electrodes may be active. Sometimes, CI users may report their auditory percept to be too soft or too loud, or to have an undesirable tonal quality (e.g. too boomy). From these reports, adjustments to the stimulation limits are normally made to optimize loudness levels (usually adjustment of M levels). For tonal adjustments, M level and/or gain adjustments would be typical. However, the process of making the percept as comfortable as possible may not necessarily be desirable in terms of long-term benefit from the device. What is immediately most comfortable may not provide the best speech understanding. This point can perhaps be clearly illustrated by the situation of fitting hearing aids to patients who have presbycusis. Such patients have often had long-term high-frequency hearing loss and tend to dislike amplified high frequencies initially, although these are critical for speech understanding.

Another difficulty is that users become adapted to a particular stimulation pattern (MAP), so that any parameter changes tend to result in an initial decrement in perceived sound quality. Because of this, patients may resist potentially beneficial modifications or may be asked to trial new MAPs for periods of days or weeks, so that the process of MAP optimization can take considerable time and sometimes numerous clinical appointments.

This traditional approach to fitting has been a legitimate one because more sophisticated methods have not been available (apart from the incorporation of objective measurements that generally aim to achieve the same goals as behavioral measures). However, in this time, clinicians working in this field have developed considerable theoretical, empirical, and heuristic knowledge such that a more systematic approach, such as is offered by FOX, might represent a significant improvement in fitting methodology and, hence, produce better outcomes.

As a way of achieving this, a fundamental principle of FOX is to make parameter adjustments that are based on outcomes, rather than channel-by-channel behavioral comfort measurements. Indeed, it seems strange to adjust such a highly technical device for such an important sensory function with only little measurable outcome as feedback. As outlined earlier, FOX can potentially use rules based on a wide range of outcome measures, including subjective questionnaires. However, the central focus is on optimization of the signal delivered by the implanted cochlea. This is the level of the auditory pathway where fitting parameters will have their most direct impact. The cochlea is responsible for detection and discrimination of the different sound features. Optimization of these processes will result in optimized identification and recognition at the higher levels of the auditory pathway that serve language processing.

Audiometry and speech discrimination tests have been used as outcome measures for many years, and so it is probably a reasonable first step to use these measures where possible. However, we now have additional outcomes that can be used. Thus, at our center, we also place considerable emphasis on the use of phoneme discrimination and loudness growth, 2 modules of the A§E psychoacoustic test suite, to gain additional information on cochlear function (as outlined in the Introduction).

As mentioned in the introduction to this report, systematizing the fitting process and reducing the interclinician variability is another important issue, especially in view of the wide range of skills and experience of the clinicians performing these tasks. There is a large number of fitting parameters available to the audiologist, some of which interact with each other. Because of this complexity, even experienced clinicians inevitably sometimes overlook potential opportunities for adjustment. Even when reliable outcome measures are available, there can be another difficulty in that the relationships between the many patient-related factors, outcome variables, and fitting parameters are very complex, making it difficult for an audiologist, in the typical clinical situation, to make systematic judgments on which parameters to adjust to gain the best outcomes.

The introduction of a system such as FOX as an "intelligent agent" using deterministic logic provides an opportunity to cope with this complexity. It is a first step toward the introduction of artificial intelligence in the fitting of CIs. At this stage, we have opted for a deterministic approach and heuristic rules in contrast to nondeterministic approaches (such as with neural networks, genetic algorithms, etc), mainly because the latter require instantaneous feedback of large amounts of outcome data. This is manageable in systems such as gaming, labyrinth tasks, pattern recognition, etc., but not in the human being where each outcome measure takes of the order of 10 minutes.

With the traditional approach to fitting, the initial stages (the period from switch-on until the EDR is stable) usually take up a lot of clinical time—perhaps 5 to 10 sessions for postlingually deafened adults and more for prelingually deaf children. Many CI users have no experience or no recollection of normal hearing, and so they are often unable to reliably make the judgments required for the audiologist to set fitting parameters. Furthermore, even if a MAP can be generated with apparently reliable estimates of the lower and upper loudness limits, there are usually large changes in these over the initial days and weeks after activation (4), meaning that measurements are often repeated at each visit and the MAP modified accordingly.

Automation and the introduction of artificial intelligence technology, such as may be provided by the use of FOX, may save a lot of time in these early stages.

The "quality" of CI fitting (i.e. outcomes) is inevitably dependent on the time spent, whatever approach is used. Figure 10 provides a hypothetic relationship where a certain amount of fitting time is needed to obtain satisfactory outcomes (solid line), but spending ever-increasing fitting time will result in diminishing returns. Naturally, we tend to favor a time input that provides the

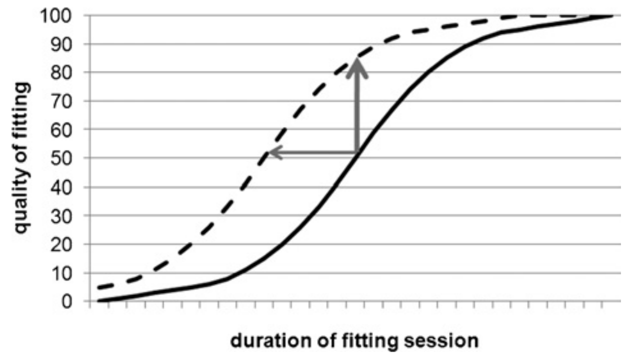

FIG. 10. Hypothetical relationship between time spent on CI fitting (abscissa) and the quality of the fitting obtained (ordinate). The *solid line* represents the relationship using the "traditional" approach to fitting, whereas the *dashed line* represents the relationship using FOX. From a starting point on the *solid line*, the incorporation of FOX can be used to either 1) spend the same amount of fitting time to achieve better outcomes or 2) spend less time to achieve the same outcome.

best compromise between time spent and quality of the outcome. From this starting point, the introduction of FOX can thus provide 2 options: either to spend the same amount of time on fitting as before and thus obtain better outcomes or to spend less time to obtain similar outcomes to before (dashed line). Again, the choice of which option to follow will typically depend on available resources, financial factors, and so on.

In addition to its application in routine clinical fitting, it is possible that the systematic approach provided by FOX may have uses in other related situations. One such application may be in clinical research, where it is conceivable to design advices to conduct clinical trials, for example, to try to find out whether the individual setting of stimulation rate can optimize results. If one designs a rule that uses an outcome to set the stimulation rate, then this can be used for driving a variety of related studies. The systematic approach will not only improve the robustness of the study design but also allow to diligently explore other MAP parameters than the ones commonly used to date.

A further advantage of the use of an intelligent agent lies in the possibility to equip it with learning skills, allowing an almost continuous improvement of the rules based on the permanently monitored effects. This could be either "case-wise," for example, where negative results in a single case can be analyzed and contribute toward rule modifications, or "group-wise," based on the statistical analysis of group data, which will allow us to expand our rules using such data both from our own center and from many others. At present, rules are only modified after the intervention of and approval by an expert team consisting of at least 1 audiologist, ear, nose, and throat specialist, and software engineer. Future developments will include automatic self-learning capacities to become part of FOX.

This report illustrates that FOX is currently an operational clinical tool, which is found useful and user-friendly by the authors. It may be the first step in a new approach to CI fitting and one which leads the way toward the use of automated expert systems. Several further developments and refinements are currently under consideration, in many cases the main task being the collection and analysis of additional fitting-related data to establish the required new rules.

These further developments include the following:

1. Refinement of current rules through analysis of additional clinical data.
2. Currently available rules are based on the expertise of our own center. In terms of AI, this is known as a "local optimum." The operation of the intelligent agent in other areas with other local optimums may expand the zone and dimensions of operation. For instance, we have already noticed that we tend to work with relatively large EDRs. Other centers often program much narrower EDRs, which may have consequences on MAP modifications to obtain a desired outcome effect.
3. We would like to conduct clinical trials in which we address a number of the currently used fitting parameters in a more systematic way. For instance, does it make a difference to systematically set the T level at 10% of the M level, to set it at higher levels or possibly to even set it to 0 CU?
4. We would like to include additional fitting parameters that have not yet been addressed at this stage. These could include stimulation rate, the choice of sequential versus simultaneous stimulation, the frequency band limits for each electrode, etc.
5. We are also keen to introduce new outcome measures such as the results of electrophysiologic tests or questionnaires, using the expertise of clinicians experienced in interpretation of such data to create rules based on these outcomes.

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