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Title: Using evoked compound action potentials to assess activation of electrodes and predict C-levels in the Tempo+ cochlear implant speech processor

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Abstract:

Objective: In this paper we analyze how electrically evoked compound action potential (ECAP) responses can be used to assess whether electrodes should be activated in the map and to estimate C-levels in the Med-El Tempo+ Cochlear Implant Speech Processor.

Design: ECAP thresholds were measured using the ECAP Recording System of the Pulsar CI^{100} implant. Twenty-one post-lingually and twenty-eight pre-lingually deafened patients participated in this study. The relationship between ECAP responses and the activation of electrodes was analyzed. Since in the Tempo+ cochlear implant speech processor an error in the estimation of T-levels (behavioral thresholds) has less effect on hearing quality than an error in the estimation of C-levels (maximum comfort levels), correlation and regression analyses were performed between ECAP thresholds and C-levels.

Results: The observation of an evoked potential generally implied that the electrode was activated, since only 3.5% of electrodes that yielded measurable evoked responses were deactivated because of collateral stimulations or an unpleasant hearing sensation. In contrast, the absence of an evoked potential did not imply that an electrode should be deactivated, since 20% of these electrodes provided a useful auditory sensation. ECAP responses did not predict the absolute behavioral comfort levels because of the excessive error between behavioral C-levels and C-levels derived from ECAP thresholds (the mean relative error is 43.78%). However, by applying a normalization procedure, ECAP measurements allowed the C-level profile to be predicted with a mean relative error of 6%; that is, they provided useful data to determine the C-level of each electrode relative to the average C-level of the patient.

Conclusions: ECAP is a reliable and useful objective measurement that can assist in the fitting of the Tempo+ cochlear implant speech processor. From results presented in this work, a protocol is proposed for fitting this cochlear implant system. This protocol facilitates appropriate cochlear implant fitting, particularly for children or uncooperative patients.

Keywords: Electrically Evoked Compound Action Potential, fitting speech processor, physiological levels, objective measurements, cochlear implant.

Text body:

INTRODUCTION

A cochlear implant is a surgically implanted electronic device that provides sound sensation to profoundly deaf patients. The speech processor of the cochlear implant must be fitted individually for each user. The fitting is performed by an audiologist trained to work with cochlear implants. The fitting of the speech processor is traditionally based on subjective responses. The most important tasks are to decide which electrodes should be activated and to establish the C-levels (maximum comfort levels) and T-levels (behavioral thresholds) of each activated electrode.

For young children or uncooperative patients, fitting the speech processor is a challenging task, because such individuals often have extremely limited expressive language skills and fitting based on subjective responses cannot be appropriately performed. Various objective physiological measures can assist in the fitting for individuals who cannot provide the necessary information, such as electrically evoked stapedial reflex (ESRT) (Hodges et al., 1997; Vargas et al., 2002; Polak et al., 2005) and electrically evoked auditory brainstem response (EABR) (Brown et al., 2000; Ruiz et al., 2002).

More recently, electrically evoked compound action potential (ECAP) measurements have been proposed (Brown et al., 2000; Cullington, 2000; Hughes et al., 2000, Smoorenburg et al., 2002, Potts et al., 2007). The ECAP is a measure of synchronous VIIIth nerve activity elicited by electrical stimulation (Franck and Norton, 2001). The typical neural response waveform is characterized by a negative peak N1 (with a latency of 0.2-0.4ms) followed by a positive peak P2 (with a latency of 0.5-0.8ms). ECAP amplitude is quantified as the amplitude difference between the N1 and P2 peaks. The ECAP amplitude is often described as a function of the stimulation level, where amplitudes increase monotonically with increasing stimulation level. From this ECAP growth function, ECAP thresholds can be determined.

Several authors have analyzed the relationship between ECAP thresholds and behavioral levels used for fitting the cochlear implant speech processor. As summarized by Hughes (2006), the correlation between ECAP thresholds and

T-levels ranges from $r=0.5$ to 0.9 (Brown et al., 2000; Cullington, 2000; Hughes et al., 2000; Franck and Norton, 2001; Thai-Van et al., 2001; Smoorenburg et al., 2002; Di Nardo et al., 2003; Polak et al., 2005). Hughes (2006) also noted that correlations between ECAP thresholds and C-levels have varied more widely across studies, from $r=0.1$ to 0.9. Brown et al. (2000) examined the responses from 44 adult Nucleus 24 cochlear implant users and found a moderate correlation coefficient of $r=0.565$ ($p<0.001$). Cullington (2000), with 55 electrodes of 8 Nucleus 24 subjects, obtained $r=0.686$ ($p<0.001$). She also emphasized that for 40% of the electrodes analyzed, the threshold necessary to record the ECAP response was greater than the maximum comfort level. Hughes et al. (2000) studied the responses from 20 children implanted with the Nucleus 24 cochlear implant. They found a correlation coefficient of $r=0.715$ ($p<0.0001$). They proposed that because of high inter-patient variability, it is necessary to combine ECAP responses with subjective responses in order for the speech processor of the cochlear implant to be fitted accurately. Brown (2003) also indicated that further research is needed in order to improve the fitting prediction algorithms based on ECAP responses. Di Nardo et al. (2003) reported more optimistic results. They analyzed the responses from 12 Nucleus 24 cochlear implant users (adults and children) and found a correlation coefficient of $r=0.721$ ($p<0.05$). Han et al. (2005) studied the responses from 8 profoundly hearing-impaired children and adults, all of whom were implanted with an Advanced Bionics system. The correlation coefficient (with 53 stimulating electrodes) was of $r=0.675$ ($p<0.001$). Polak et al. (2005), considering the responses from 30 adults with Nucleus 24 cochlear implant, obtained a higher correlation coefficient of $r=0.85$ ($p<0.05$). King et al. (2006)

undertook a study with 21 adult recipients of the Nucleus 24 device in order to develop reliable predictors of C-levels from ECAP. They found that the ECAP threshold (all electrodes) and slope of the growth function (electrodes seven and nine, only) measures were significant predictors (r ranging from 0.625 to 0.877, $p<0.05$). They reported that these measures may provide an alternative means of predicting C-levels when no other measures are available. Caner et al. (2007) studied the responses from 15 pediatric CII Advanced Bionics implant users. They found a moderate correlation coefficient of $r=0.479$ ($p<0.05$). Potts et al. (2007) found a correlation coefficient of $r=0.69$ ($p<0.05$) analyzing the responses from 12 adult Nucleus 24 cochlear implant recipients. They highlighted the existence of particular subjects for which an accurate prediction of C-levels was not possible.

Other authors are more pessimistic with regard to the inference of C-levels from ECAP thresholds. Considering 20 adult patients with the Nucleus 24 cochlear implant, Franck and Norton (2001) obtained a non-significant correlation coefficient of $r=0.09$ ($p=0.199$). Thai-Van et al. (2001), examining the responses from 23 children with the Nucleus 24 cochlear implant, found a significant correlation for all tested electrodes at 12 months post-implantation (r ranging from 0.691 to 0.966), but not at 6 and 9 months post-implantation. Smoorenburg et al. (2002) maintained that C-levels cannot be predicted from ECAP thresholds. Analyzing 13 post-lingually deafened patients wearing the Nucleus 24 cochlear implant, they found a correlation coefficient of $r=0.39$ ($p<0.05$).

When an automatic method is applied in order to predict T- and C-levels, the impact that a wrong estimation of these fitting levels has over sound perception should be evaluated (Seyle and Brown, 2002; Willeboer and Smoorenburg, 2006). The effect depends on the signal processing performed by the cochlear implant and it varies among different cochlear implant systems. In cochlear implant systems, acoustic amplitudes within a specific acoustic (input) dynamic range are mapped onto the 10-20dB range of electric stimulation (Zeng et al., 2002). The range of electric currents is determined by the clinically measured T- and C-levels. Once the electrical dynamic range is fixed, the mapping is completely determined by the input range of acoustic amplitudes and the mapping function (Fu and Shannon, 1999). Owing to specific features of the Tempo+ cochlear implant processor (Med-El, Innsbruck, Austria), accuracy in the estimation of C-levels is more critical than for T-levels, and hearing quality is only slightly degraded when T-levels are not accurately fitted (Sainz et al., 2003). This is a substantial difference of Med-El implant systems compared with Nucleus systems in which estimation of T-levels is more critical (Zierhofer, 2003; Dawson et al., 2007).

The results provided by other studies regarding the relationship between ECAP thresholds and subjective fitting levels performed with other cochlear implant systems cannot directly be applied to the Med-El system, because of its specific characteristics. Therefore, a study that relates ECAP with subjective fitting levels is necessary in order to analyze possible applications for fitting the Med-El cochlear implant system. Considering that an error in the estimation of T-levels is less critical than an incorrect inference of C-levels in the Tempo+ cochlear implant speech processor, this paper focuses on the use of ECAP measurements for (1) the assessment of which electrodes should be activated, and (2) determination of appropriate C-levels.

MATERIAL AND METHODS

A. Subjects

Forty-nine patients, 21 females and 28 males, aged at ECAP testing from 1 to 67 years (with a mean age of 15 years) participated in this study. All subjects were implanted with the Med-El Pulsar CI^{100} implant device at San Cecilio University Hospital, Granada (Spain). 21 patients were post-lingually deafened, and 28 patients were pre-lingually deafened. Out of a total of 588 electrodes (12 electrodes per patient), 529 were activated. ECAP recordings were obtained between 3 and 60 months after the first fitting while patients were awake. Hearing loss etiology and progression characteristics varied across subjects. Details of the study population are summarized in table 1.

B. ECAP Recording

The Med-El Pulsar CI^{100} consists of a receiver-stimulator, 12 intra-cochlear electrodes and one additional extra-cochlear ground electrode. This implant allows communication of data between the external speech processor and the implant using transcutaneous radio-frequency transmission. ECAP recordings were acquired using the ECAP Recording System (EAPRS) integrated in the

Med-El Pulsar CI^{100} system and the ArtResearch software (Spitzer et al., 2006). Whole-nerve action potentials were evoked by electrical stimulation applied on a given intra-cochlear electrode in monopolar stimulation mode. The implant records those potentials from a neighboring electrode, amplifies the recorded signal and encodes it for radio-frequency transmission back to the speech processor.

ECAP responses were evaluated for all electrodes. The corresponding recording site was one electrode apical to the stimulation site. For electrode 1 (the most apical one) the recording site was electrode 2. The procedure for stimulation and ECAP recording utilizes: (1) stimulation rate of 50 Hz: biphasic stimulation pulses were presented every 20ms; (2) sampling delay of 125 μs: the input of the amplifier is in short-circuit for 125 μs after the beginning of the stimulation pulse; (3) pulse amplitudes ranging from 0 to 1200 μA and pulse durations ranging from 30 to 45 μs/phase; duration was initially set to 30 μs/phase and when no response was observed by visual detection at a stimulus amplitude of 1200 μA, it was progressively increased until the subject indicated discomfort; (4) 50 sweeps: in order to obtain an ECAP measurement, we averaged 50 anodic/cathodic and 50 cathodic/anodic responses (ensemble averaging method); (5) artifact reduction based on generalized alternating stimulation (Alvarez et al., 2007), in which responses to anodic/cathodic and cathodic/anodic stimulation pulses are combined using weights that generally are different than 0.5.

Figure 1 shows a series of ECAP responses acquired in amplitude growth mode (increasing the stimulation level) for one of the patients included in this study. The stimulation level, Q, is defined as the product:

$$Q = T_s \cdot I_s \qquad (1)$$

where T_s is the duration (in μs) of each phase of the biphasic pulse, I_s is the amplitude in current units (in μA) of the stimulation pulses and Q is expressed in charge units (nanoCoulomb, nC).

The amplitude of the ECAP response was calculated as the difference between the peak P2 and the peak N1. Figure 2 shows the amplitude growth function for the electrode and patient considered in figure 1. The amplitude growth function represents the amplitude of the evoked response as a function of the applied stimulation level. From the amplitude growth function, ECAP threshold (T_{ECAP}) can be defined as the lowest stimulation level that elicited an evoked response observed by visual inspection (which corresponds to a value of 15nC for the electrode and patient shown in figure 2).

C. Fitting levels

All patients were first fitted with the Tempo+ speech processor using the CI Studio+ software at approximately 1 month after implantation. Behavioral measures of T- and C-levels were obtained by an audiologist with 5 years' experience in fitting cochlear implant users. Each patient underwent at least 9 fitting sessions and maintained stable C-levels for at least one month before

ECAP data collection. Maps were updated immediately before the ECAP recording session. At the time of fitting, the audiologist had no knowledge of the ECAP thresholds.

In adult patients, all electrodes for which the subjects could hear sound were activated. In children or uncooperative patients, the electrodes that caused an observable behavioral response were activated. If an electrode provided facial stimulation, painful percepts, unpleasant hearing or a clearly elevated threshold compared to other electrodes, it was deactivated.

The stimuli used to determine behavioral C-levels consisted of a train of biphasic pulses presented in monopolar mode at a rate of approximately 1000 Hz. Duration and amplitude of the biphasic pulses was varied from 24.17 to 86.67 µs/phase and from 0 to 1200 µA, respectively. Duration of the pulse train was 50 ms. C-levels were fitted by using ascending loudness judgments. For adult patients, the C-level for each electrode was set to the highest stimulation level that produced loud but comfortable sound. In young subjects, the C-level was set at about 90% of the stimulation level that caused behavioral responses indicating discomfort. In addition, the C-levels for each electrode were balanced for equal loudness. C-levels provided by the audiologist were considered as a reference when comparing C-levels derived from ECAP measurements.

RESULTS

A. Activation of electrodes

The 49 patients considered in this paper had a total of 588 electrodes (12 electrodes per patient). Table 2 shows the relationship between the activation of these electrodes and the existence of an identifiable ECAP response. From this table, we can calculate the following conditional probabilities:

$$P(\text{ON} \mid \text{ECAP}) = 96.5\,\% \quad (519/538) \tag{2}$$

$$P(\text{OFF} \mid \text{ECAP}) = 3.5\,\% \quad (19/538) \tag{3}$$

$$P(\text{ON} \mid \text{NoECAP}) = 20.0\,\% \quad (10/50) \tag{4}$$

$$P(\text{OFF} \mid \text{NoECAP}) = 80.0\,\% \quad (40/50) \tag{5}$$

where P(A|B) represents the probability of A given B. Analyzing our results we can observe:

- The high value of P(ON|ECAP) indicates a strong association between electrodes that generate an ECAP response and electrodes that provide useful stimulation of the auditory nerve.
- P(OFF|ECAP) represents false positives. Although these electrodes yielded measurable evoked responses, they were deactivated because they provided collateral stimulations of the facial nerve (as was the case of patient 35, electrodes 9, 10 and 11) or an unpleasant hearing sensation (as occurred with the most basal electrodes in several patients).

- Most (80%) of the electrodes presenting no ECAP response did not provide usable auditory sensations (for example, those electrodes allocated outside the cochlea or with high impedance) and were deactivated in the clinical map.
- The relatively high value of P(ON|NoECAP) (false negatives) should be noted. This probability represents electrodes activated despite having no identifiable evoked response. This can be explained by the existence of electrodes for which ECAP thresholds were greater than the maximum levels tolerated by the patient (Cullington, 2000), probably because of poor synchronization of the responses of different activated neurons (Lai and Dillier, 2005) or because C-levels were elicited by a faster stimulation rate than the one used for ECAP measurements (Hughes et al., 2000; Skinner et al., 2000; Potts et al., 2007).

Based on the above findings, the observation of an evoked potential generally implies that the electrode should be activated. In only 3.5% of cases were these electrodes deactivated owing to collateral stimulations or an unpleasant hearing sensation. In contrast, the absence of an evoked potential does not imply that an electrode should be deactivated, since 20% of the electrodes without an observable ECAP response provide a useful hearing sensation.

B. Inference of C-levels

1) Relationship between ECAP thresholds and C-levels

All patients included in this study presented an identifiable ECAP response for at least 8 electrodes. Across all subjects, it was possible to record ECAP responses for 538 electrodes out of a total of 588 tested electrodes (91.5%). The mean and standard deviation of ECAP thresholds across electrodes and patients for pre- and post-lingual subjects were (18.19nC, 6.28nC) and (18.85nC, 7.41nC), respectively. We found no statistically significant differences between the two groups regarding ECAP thresholds (matched pair Student t-test, p=0.27). On the other hand, C-levels measured by the audiologist were found to be greater in pre-lingual than in post-lingual patients (matched pair Student t-test, p=0.002). The mean and standard deviation of C-levels for pre- and post-lingual subjects were (35.73nC, 20.56nC) and (30.49nC, 15.81nC), respectively.

Figure 3 shows the relationship between behavioral C-levels measured by the audiologist and ECAP thresholds for pre-lingually (upper panel) and post-lingually (lower panel) deafened subjects. ECAP thresholds exceeded C-levels for 28 electrodes of pre-lingual subjects and 40 electrodes of post-lingual subjects. Table 3 (upper three rows) summarizes the results of linear regression analysis for both groups. According to these results, C-levels for a pre-lingually deafened patient can be estimated using the following expression:

$$\text{C-level(predicted)} = 2.03 \cdot T_{ECAP} - 1.18 \ \ (\pm 31.56) \tag{6}$$

The corresponding expression for a post-lingually deafened subject is:

$$\text{C-level(predicted)} = 0.99 \cdot T_{ECAP} + 11.76 \ \ (\pm 27.35) \tag{7}$$

where C-level(predicted) indicates that these C-levels are inferred from ECAP thresholds using the regression analysis. Both C-level(predicted) and T_{ECAP} parameters are expressed in nC. The 95% confidence interval (in nC) is shown in parentheses.

Figure 4 shows ECAP thresholds (T_{ECAP}), C-levels measured by the audiologist (C-level(audiologist)) and C-levels predicted from ECAP thresholds (C-level(predicted)) for patients 13 and 26 (pre-lingually deafened subjects) and for patients 36 and 45 (post-lingually deafened subjects). As can be observed, C-level(predicted) follows the contour of T_{ECAP} , even though different coefficients are applied in the case of pre- and post-lingual subjects (according to equations (6) and (7)), and therefore the relationship between T_{ECAP} and C-level(T_{ECAP}) is different for the two groups. When using T_{ECAP} to infer C-levels, particular attention should be paid to the error between C-levels estimated from T_{ECAP} and those measured by the audiologist. In figure 4, we have selected two patients (26 and 45) for whom the error is small, and two patients (13 and 36) for whom the error is larger. For the latter two patients, using a map based on T_{ECAP} would be unacceptable (in these patients C-levels predicted from T_{ECAP} are about twice those measured by the audiologist).

Previous studies conducted with Nucleus 24 (Cullington, 2000; Hughes et al., 2000; Potts et al., 2007) and Advanced Bionics (Caner et al., 2007) devices demonstrated that because the inter-patient variability is high, C-levels cannot be predicted accurately from ECAP thresholds. In order to assess the accuracy of C-levels predicted from ECAP thresholds in the Med-El device, we propose using the relative error. It can be calculated as:

$$\mathrm{RE}_{\text{C-level}} = \frac{\left| [\text{C - level(predicted)}] \text{ - } [\text{C - level(audiologist)}] \right|}{[\text{C - level(audiologist)}]} \tag{8}$$

where | . | represents absolute value. The mean and standard deviation of the relative error for pre- and post-lingual groups are (42.70%, 38.59%) and (45.22%, 36.33%), respectively. We found no statistically significant differences in the relative error between the two groups (matched pair Student t-test, p=0.45). Figure 5 shows the cumulative histogram of the relative error for the pre-lingual (solid line) and post-lingual (dashed line) subjects considered in this study. In the pre-lingual group 50% of cases showed relative errors greater than 31.10% and 5% showed errors greater than 124.80%. In the post-lingual group, 50% of cases showed relative errors greater than 36.37% and 5% showed errors greater than 119.86%. Table 4 (upper three rows) shows the results of a statistical analysis of the relative error (including mean, standard deviation and 50th, 80th and 95th percentiles) for pre- and post-lingual groups, as well as for the two groups combined.

This analysis shows that, although there is an appreciable correlation and a statistical dependence between the ECAP thresholds and C-levels for pre-lingual (r=0.62, p<0.0001) and post-lingual (r=0.47, p<0.0001) subjects, the ECAP thresholds cannot be used to predict C-levels. A fitting map based on the ECAP thresholds is not trustworthy, since the relative error is less than 20% for only 28.95% and 27.03% of the electrodes for the pre- and post-lingual groups, respectively, and as discussed in a previous paper (Sainz et al., 2003) an error of 20% in the estimation of C-levels significantly reduces hearing quality. Table 5 (“Without Normalization” column) shows the mean and maximum relative error and the number of electrodes with a relative error greater than 20% for all subjects in this study. The mean, the standard deviation and the 95th percentile for pre-lingual, post-lingual and all subjects are also indicated. We can observe that if C-levels are predicted from ECAP thresholds in the Med-El device, the expected relative error is greater than 42% (in both pre- and post-lingual subjects) and an inappropriate C-level (relative error greater than 20%) is expected for more than 7 electrodes (of a total of 12) in each patient, which is obviously unacceptable as a fitting procedure.

2) Analysis using normalized values

Although ECAP thresholds cannot be used to predict C-levels accurately, several studies have shown that they may assist in fitting the speech processor (Brown et al., 2000; Hughes et al., 2000; Di Nardo et al., 2003; McKay, 2005; King et al., 2004; King et al., 2006). Brown et al. (2000) and Hughes et al. (2000) proposed an ECAP-based fitting procedure for the Nucleus device. This procedure sets the relative amplitude of map C-levels using the ECAP threshold profile and then globally shifts all C-levels according to the subject's behavioral responses. In this section an ECAP-based fitting procedure for the Med-El cochlear implant system is presented. The proposed method makes use of the relationship between the normalized C-levels and the normalized ECAP thresholds to predict the contour of C-levels. Normalization is performed by dividing each C-level (or T_{ECAP}) by the average C-level (or the average T_{ECAP}) of the patient. The following equations indicate the proposed normalized parameters:

$$\text{Norm.C - level} = \frac{\text{C - level}}{\text{Avg.C} - \text{level}} \quad (9)$$

and

$$\text{Norm.T}_{\text{ECAP}} = \frac{\text{T}_{\text{ECAP}}}{\text{Avg.T}_{\text{ECAP}}} \quad (10)$$

where Avg.x indicates variable x averaged for all the electrodes presenting an identifiable ECAP response for a given patient.

Figure 6 shows the relationship between the normalized C-levels fitted by the audiologist and the normalized ECAP thresholds for the 28 pre-lingual (upper panel) and 21 post-lingual (lower panel) subjects considered in this study. Table 3 (lower three rows) shows the results of linear regression analysis using normalized values for pre-lingual, post-lingual and all subjects. We found statistically significant correlation coefficients of r=0.71 and r=0.62 in pre- and post-lingual subjects, respectively.

From the results in table 3, the normalized C-levels for a pre-lingually deafened patient can be predicted using the following expression:

$$\text{Norm.C - level(predicted)} = 0.34 \cdot \text{Norm.T}_{\text{ECAP}} + 0.66 \ (\pm 0.11) \quad (11)$$

The corresponding expression for a post-lingually deafened subject is:

$$\text{Norm.C - level(predicted)} = 0.54 \cdot \text{Norm.T}_{\text{ECAP}} + 0.46 \ (\pm 0.22) \quad (12)$$

where Norm.C-level(predicted) and Norm.T_{ECAP} parameters have no units as they are normalized variables. The 95% confidence interval is shown in parentheses.

Figure 7 shows the normalized C-levels measured by the audiologist (Norm.C-level(audiologist)), the ECAP-based normalized C-levels using the regression analysis (Norm.C-level(predicted)) and the normalized ECAP thresholds (Norm.T_{ECAP}) for the same patients shown in figure 4. Comparing figures 4 and 7, we can observe that although the audiologist and T_{ECAP}-derived C-levels may differ substantially, the ECAP-based normalized C-levels predicted using the regression analysis are very close to the audiologist-set normalized C-levels.

The relative error between the audiologist and T_{ECAP}-derived normalized C-levels can be calculated as:

$$\mathrm{RE}_{\mathrm{Norm.C\text{-}level}} = \frac{\left|[\mathrm{Norm.C\text{-}level(predicted)}] - [\mathrm{Norm.C\text{-}level(audiologist)}]\right|}{[\mathrm{Norm.C\text{-}level(audiologist)}]} \qquad (13)$$

where | . | represents absolute value.

Figure 8 shows the cumulative histogram of the relative error for the ECAP-based normalized C-levels of the pre-lingually (solid line) and post-lingually (dashed line) deafened subjects considered in this study. Table 4 (lower three rows) shows the results of a statistical analysis of the relative error (including mean, standard deviation and 50^{th}, 80^{th} and 95^{th} percentiles) for pre- and post-lingual groups, as well as for patients in both groups. We can observe that the mean relative error is only 4.24% and 8.36% for pre- and post-lingual subjects, respectively. The contour of C-levels in pre-lingual patients can be predicted using the proposed method with an error smaller than 12.36% in 95% of cases (smaller than 3.06% in 50% of cases). Regarding post-lingually deafened patients, the contour of C-levels can be estimated with an error smaller than 23.16% in 95% of cases (smaller than 6.54% in 50% of cases). We also found that the relative error of the predicted normalized C-levels is smaller in pre-lingual than in post-lingual subjects (matched pair Student t-test, $p<0.0001$).

Although these global results suggest that ECAP measurements allow the C-level profile to be predicted accurately, a more detailed analysis of individual subjects has been performed. The relative error for each subject when the C-level profile is predicted using the proposed ECAP-based fitting procedure is shown in table 5 (last column). The mean and maximum relative error and the number of electrodes with a relative error higher than 20% are shown for each patient. We can observe that only 12 patients (2 pre-lingual and 10 post-lingual) have an electrode that is not well- fitted if the C-level profile is predicted by the proposed ECAP-based fitting procedure. Patient 30 cannot be accurately fitted using the proposed normalization procedure as he has 4 electrodes with a relative error higher than 20%, and the maximum relative error is higher than 80%. Table 5 also shows the mean, the standard deviation and the 95^{th} percentile of the mean relative error, the maximum relative error and the number of not well- fitted electrodes for pre-lingual, post-lingual and all subjects considered in this study. The mean relative error (averaged among patients) is only 4.2% and 8.2% for pre- and post-lingual subjects, respectively. The maximum relative error (averaged among patients) is only 10.5% and 20.9% for pre- and post-lingual patients. These results suggest that ECAP thresholds provide valuable information for setting C-level profiles in the fitting maps.

DISCUSSION

This paper proposes the use of the ECAP responses to assess whether electrodes should be activated and to estimate C-levels of the Tempo+ cochlear implant speech processor. According to our results, an electrode yielding an ECAP threshold at amplitudes that can be tolerated by the patient should generally be activated. Only 3.5% of electrodes that yielded measurable evoked responses were deactivated due to collateral stimulations or an unpleasant hearing sensation. However, the absence of an evoked potential does not imply that an electrode should be deactivated, since 20% of electrodes without evoked responses were activated. In these cases, the evoked potential thresholds were higher than the maximum levels tolerated by the patients, probably because behavioral comfort levels were elicited by a faster stimulation rate than the one used to elicit ECAP responses (Hughes et al., 2000; Skinner et al., 2000; Potts et al., 2007) or because of poor synchronization of responses from the different activated neurons (Lai and Dillier, 2005). Therefore, if an electrode does not yield an ECAP response, additional tasks should be performed to determine whether the electrode should be activated; these might include behavioral responses or the recording of other types of electrophysiological measures (EABR or ESRT) (Hodges et al., 1997; Brown et al., 2000; Ruiz et al., 2002; Vargas et al., 2002; Polak et al., 2005).

In this paper we have focused on the relationship between T_{ECAP} and C-levels. We have paid no attention to the relationship between T_{ECAP} and T-levels because T-levels are not particularly relevant for hearing quality in the Tempo+

cochlear implant processor (Sainz et al., 2003). Most researchers investigating the inference of fitting parameters from ECAP responses have used the Nucleus 24 cochlear implant (Brown et al., 2000; Cullington, 2000; Hughes et al., 2000; Franck and Norton, 2001; Thai-Van et al., 2001; Smoorenburg et al., 2002; Di Nardo et al., 2003; Polak et al., 2005; Potts et al., 2007). Because of the specific characteristics of the Med-El cochlear implant system, studies such as the one presented in this paper are necessary in order to analyze the relationship between ECAP responses and fitting maps in this cochlear implant system.

In our study, the correlation coefficient between T_{ECAP} and C-levels is r=0.53, which is similar to the correlation coefficients found in other studies for the Nucleus 24 (Brown et al., 2000; Cullington, 2000; Di Nardo et al., 2003) and Advanced Bionics (Han et al., 2005; Caner et al., 2007) devices. For pre-lingually deafened patients, the correlation coefficient is higher than for post-lingually deafened patients (r=0.62 and r=0.47 for pre- and post-lingual groups, respectively). These results are consistent with Morita et al. (2003). They suggest that the stronger correlation between ECAP thresholds and behavioral C-levels in pre-lingually (r=0.545) compared with post-lingually (r=0.349) deafened patients in their study might result from differences in how pre- and post-lingual subjects define loudness and/or how the audiologist uses the patient reactions to set C-levels.

Regression analysis provides a procedure for estimating C-levels from ECAP thresholds (King et al., 2006). However, the accuracy of such C-level estimates must be considered. Several studies of the application of ECAP thresholds to predict fitting maps conclude that ECAP thresholds are valuable in the absence of subjective responses (McKay, 2005; King et al., 2004; King et al., 2006), but that fitting maps provided by the audiologist support better speech perception (or similarly, depending on the test conditions) than those derived from ECAP thresholds (Seyle and Brown, 2002; Willeboer and Smoorenburg, 2006). For this reason, we have considered the audiologist's C-levels as our reference, evaluating the accuracy in the prediction of the fitting maps in terms of the relative error between ECAP-derived C-levels and those provided by the audiologist. Even though correlation coefficients are moderate for both pre- and post-lingual groups, the relative error of ECAP-derived C-levels is too high for a reliable prediction of the maps. An individual subject analysis reveals that the mean relative error is higher than 42% in both groups and that, on average, predicted C-levels are expected to be unacceptable (relative error higher than 20%) for more than 7 electrodes (of a total of 12 in the studied device) for a given patient.

The poor accuracy in the prediction of the maps is associated with a high inter-patient variability (Hughes et al., 2000; Smoorenburg et al., 2002; Potts et al., 2007). In order to deal with inter-patient variability some authors (Brown et al., 2000; Hughes et al., 2000) proposed combining ECAP responses with subjective responses. In this fitting procedure, implemented on the Nucleus device, the predicted C-levels are essentially the ECAP threshold function shifted according to the subject's behavioral responses. Franck (2002) proposed adding ECAP growth function data to set the C-level profile. On the other hand, Smoorenburg et al. (2002) analyzed the slopes in C-levels and

ECAP thresholds across electrodes within each subject. They found that the correlation between the ECAP thresholds and the maximum stimulation levels was poor with respect to both overall level and slope (r=0.39 and r=0.36, respectively). Holstad et al. (2009) examined the relationship between ECAP thresholds and C-levels in pre/perilinguistically deaf children. They found that the profile of ECAP thresholds did not follow the profile of C-levels across electrodes for most children and simply shifting the ECAP profile to set C-levels would therefore result in a loudness imbalance between electrodes.

In this paper an ECAP-based fitting procedure for Med-El cochlear implant systems is proposed. The fitting procedure proposed by Brown et al. (2000) and Hughes et al. (2000) sets the C-level profile using directly the ECAP threshold profile and then globally shifts all C-levels according to the subject's behavioral responses (that is, the average C-level of the patient is added to the C-level profile). In contrast, the proposed ECAP-based fitting procedure predicts the contour of C-levels using a regression analysis based on the normalization of both C-levels and ECAP thresholds. Absolute C-levels are then increased until the global stimulation level is appropriate for the subject (that is, the C-level profile is multiplied by the average C-level of the patient). Since Nucleus cochlear implant systems use logarithmic current steps (Clark, 2003; Botros et al., 2007) and Med-El devices use linear units of charge (Zierhofer, 2003), the two fitting procedures are similar in terms of loudness increment. The main difference between the two procedures is that a regression equation to predict the contour of C-levels is applied in the proposed ECAP-based fitting procedure.

The regression analysis performed in the proposed ECAP-based fitting procedure is based on the normalization of both C-levels and ECAP thresholds, by dividing the specific values for each electrode by the average over all the patient's electrodes. Regression analysis over normalized parameters reveals correlation coefficients of r=0.71 and of r=0.62 in the pre- and post-lingual group, respectively. An individual subject analysis shows that 12 patients (2 pre-lingual and 10 post-lingual) have an inappropriate profile at some electrode if the C-level contour is predicted using the proposed method. All of these electrodes present a relative error slightly greater than 20% (less than 32%) except for one patient. This patient could not be accurately fitted using the ECAP-based C-level profile. The existence of particular subjects for which an accurate profile from ECAP is not possible is in accordance with results reported by Potts et al. (2007). We can observe that the mean relative error is only 4.2% and 8.2% for pre- and post-lingual subjects, respectively. The maximum relative error is 10.5% and 20.9% for pre- and post-lingual patients, respectively. The reduction in inter-patient variability achieved with the proposed normalization procedure allows an accurate prediction to be made of the normalized C-levels, which can be used for setting relative C-levels in the fitting maps, that is, to determine the C-level of each electrode relative to the average C-level for the patient. This is particularly interesting for pre-lingual or uncooperative patients as they have unreliable behavioral responses and fitting based on subjective responses cannot always be appropriately performed.

Based on our results, a protocol can be derived to fit the Tempo+ cochlear implant speech processor based on ECAP responses. The first task is to decide whether any electrodes should be deactivated. According to our results, ECAP responses assist in the decision about activating an electrode. If a certain electrode yields an ECAP response, that electrode should generally be activated. However, if an electrode does not yield an ECAP response, additional measures should be performed in order to decide whether the electrode should be activated.

ECAP responses may also assist in fitting C-levels. They can be calculated with a confidence interval of 95% using equations (6) and (7) for pre- and post-lingually deafened patients, respectively. Thus, the ECAP thresholds allow C-levels to be predicted, but with a considerable margin of error (the relative error is greater than 20% in 70% of cases). Owing to the high value of this error, ECAP thresholds should not be used to predict C-levels. However, normalized ECAP thresholds allow normalized C-levels to be predicted accurately, which can be used for setting the C-level profile. The normalized C-levels of pre- and post-lingual subjects can be predicted with an error of less than 12.36% and 23.16% in 95% of cases, respectively, using equations (11) and (12). Thus, the profile predicted from ECAP thresholds can be used to set initial C-levels. Based on the subject’s behavioral responses, the global volume of the speech processor may then be progressively increased until the global stimulation level is appropriate for the subject.

In adult patients, T-levels can be established using a slightly smaller value than the lowest stimulation level at which the subjects could hear sound. In children or uncooperative patients, T-levels can be set up to a significantly smaller level at which an observable behavioral response is obtained (such as quieting or head turning). In any case, a small enough T-level should be set. In the absence of behavioral information, a reasonable value for T-levels could be about 5% of C-levels (Sainz et al., 2002), or a null value could even be set for T-levels, since it reduces sensitivity by only about 10dB (Sainz et al., 2003).

This fitting protocol can easily be added to the speech processor fitting procedure. Since the ECAP Recording System is integrated into the cochlear implant software, procedures to record ECAP responses are relatively simple and quick to perform. The addition of the ECAP measurements provides useful information for fitting a cochlear implant processor, which is of particularly interest in patients whose behavioral responses are inconsistent or unreliable.

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Figure Legends

- Figure 1. ECAP responses acquired with increasing stimulation level, for electrode 9 of patient 43.
- Figure 2. Amplitude growth function for electrode 9 of patient 43.
- Figure 3. Relationship between the ECAP thresholds and C-levels measured by the audiologist in 28 pre-lingual (upper panel) and 21 post-lingual patients (lower panel). The regression line (solid line) and the 95% confidence interval (dashed lines) provided by linear regression analysis are also shown.
- Figure 4. ECAP thresholds (T_{ECAP}), C-levels estimated by the audiologist (C-level(audiologist)) and C-levels predicted from ECAP thresholds (C-level(predicted)) for two pre-lingually deafened patients (upper panel) and two post-lingual subjects (lower panel).
- Figure 5. Cumulative histogram of the relative error for C-levels of the pre-lingually (solid line) and post-lingually (dashed line) deafened subjects considered in this study.
- Figure 6. Relationship between the normalized ECAP thresholds and normalized C-levels in 28 pre-lingual (upper panel) and 21 post-lingual patients (lower panel). The regression line (solid line) and the 95% confidence interval (dashed lines) provided by linear regression analysis are also shown.
- Figure 7. Normalized ECAP thresholds (Norm.T_{ECAP}), normalized C-levels estimated by the audiologist (Norm.C-level(audiologist)) and normalized C-levels predicted from ECAP thresholds using the proposed method (Norm.C-

level(predicted)) for two pre-lingually deafened patients (upper panel) and for two post-lingual subjects (lower panel).

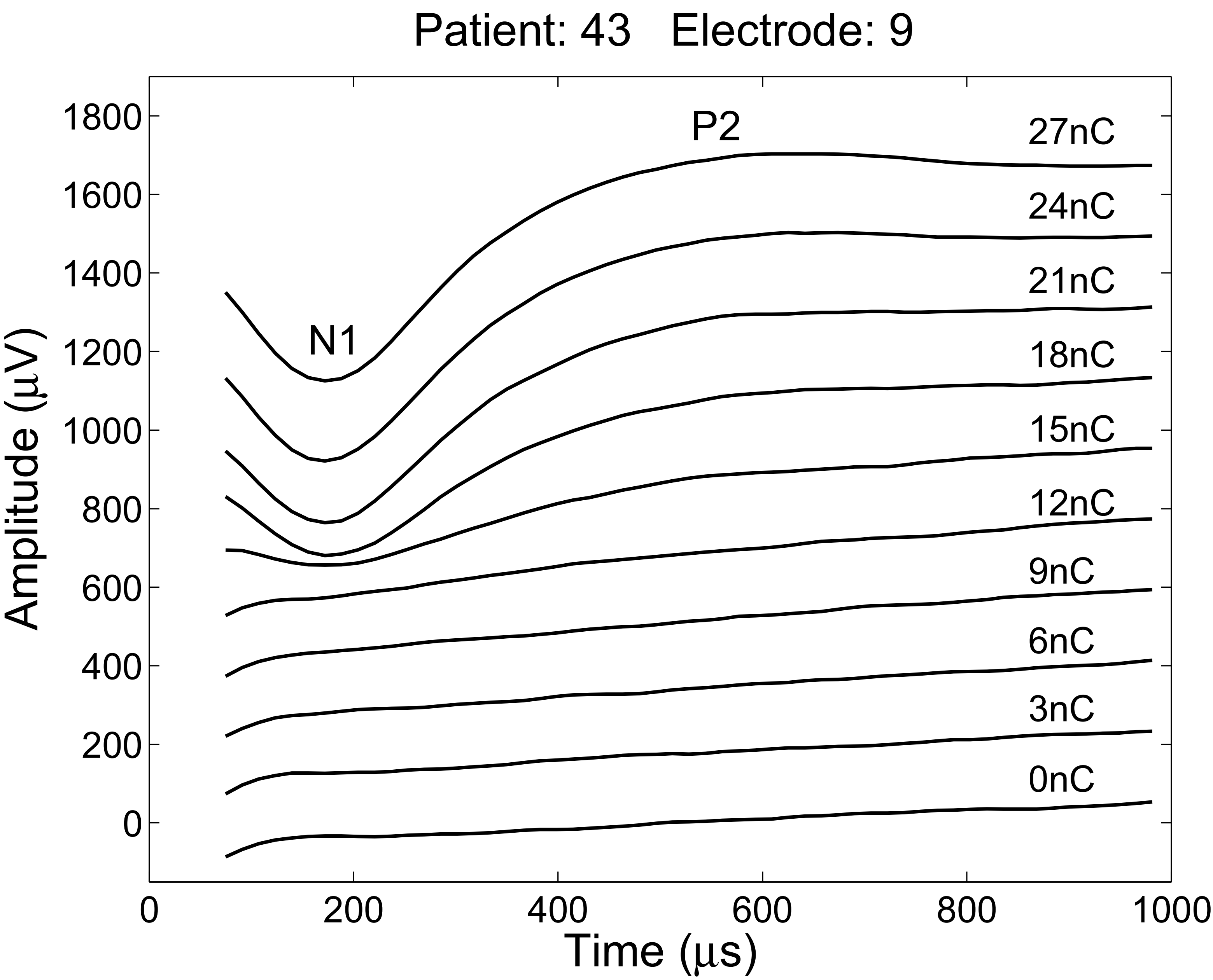
- Figure 8. Cumulative histogram of the relative error for ECAP-based normalized C-levels of the pre-lingually (solid line) and post-lingually (dashed line) deafened subjects considered in this study.

Table Legends

- Table 1. Profiles of all subjects in this study.
- Table 2. Number of electrodes activated and deactivated (ON/OFF), presenting and not presenting ECAP response (ECAP/NoECAP).
- Table 3. Results of the regression analysis for pre-lingual, post-lingual and all patients considered in this study. N represents the number of electrodes, a and b indicate the slope and the y-intercept of the regression line, respectively. SE(a) and SE(b) are the standard errors of a and b, respectively. The parameters r, R^2 and p are the correlation coefficient, the coefficient of determination and the probability associated with the null hypothesis of statistical independence, respectively. The semi-width of the 95% confidence intervals is also shown.
- Table 4. Analysis of the relative error of ECAP-based C-levels (upper three rows) and normalized C-levels obtained using the proposed ECAP-based fitting procedure (lower three rows) for pre-lingual, post-lingual and all subjects included in this study. The number N of electrodes, the mean and the standard deviation of the relative error are indicated. P_{50}, P_{80} and P_{95} are the 50th, 80th and 95th percentiles, respectively.

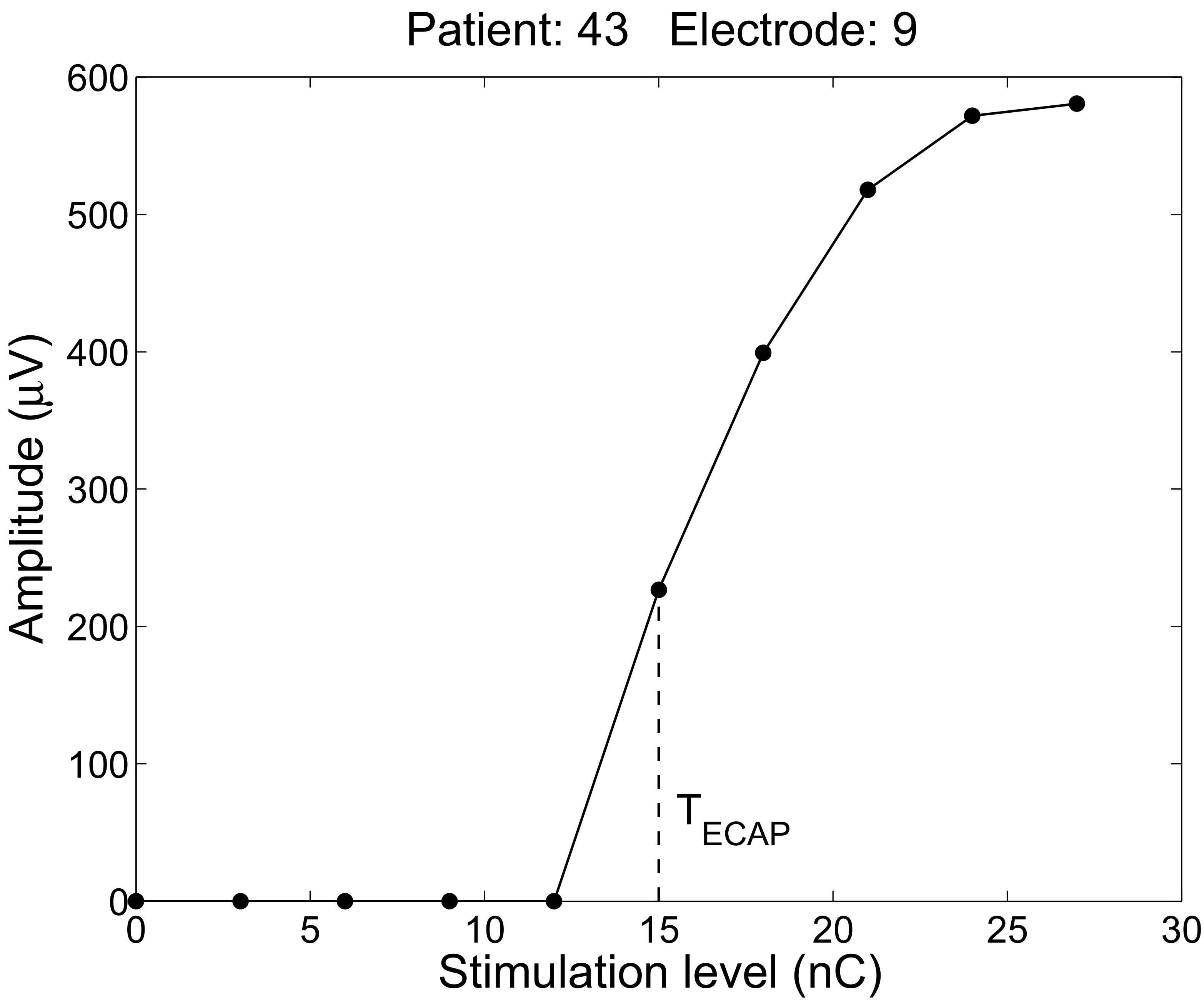
- Table 5. Individual subject analysis of the error associated with the ECAP-based C-levels (left column) and with the C-level profiles predicted by the proposed ECAP-based fitting procedure (right column). N represents the number of active electrodes. The mean and maximum relative error and the number of electrodes with an error higher than 20% are shown. The mean, the standard deviation and the 95th percentile for pre-lingual, post-lingual and all subjects are also indicated.

Figure1



Patient: 43 Electrode: 9
Amplitude (μV)
Time (μs)
0
200
400
600
800
1000
1200
1400
1600
1800
0
200
400
600
800
1000
N1
P2
27nC
24nC
21nC
18nC
15nC
12nC
9nC
6nC
3nC
0nC

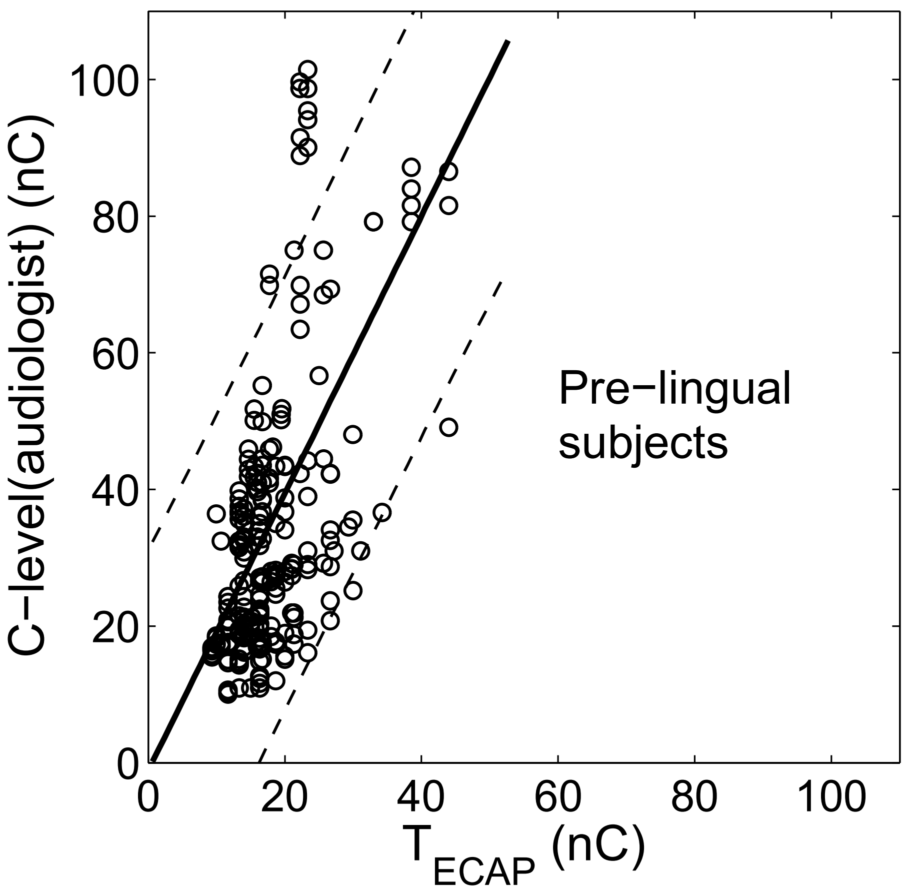
Figure2



Patient: 43   Electrode: 9
600
500
400
300
200
100
0
Amplitude (µV)
0
5
10
15
20
25
30
Stimulation level (nC)
T_{ECAP}

Figure3

N=297 r=0.62 R^2=0.38 p<0.0001



N=222 r=0.47 R^2=0.22 p<0.0001

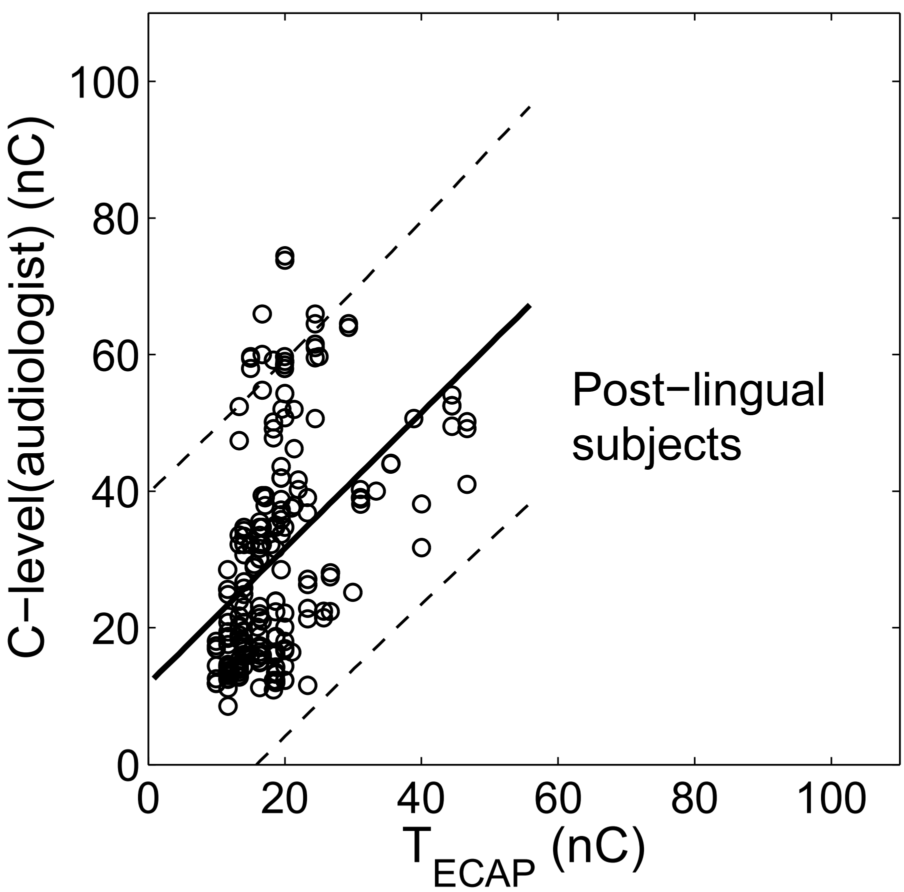
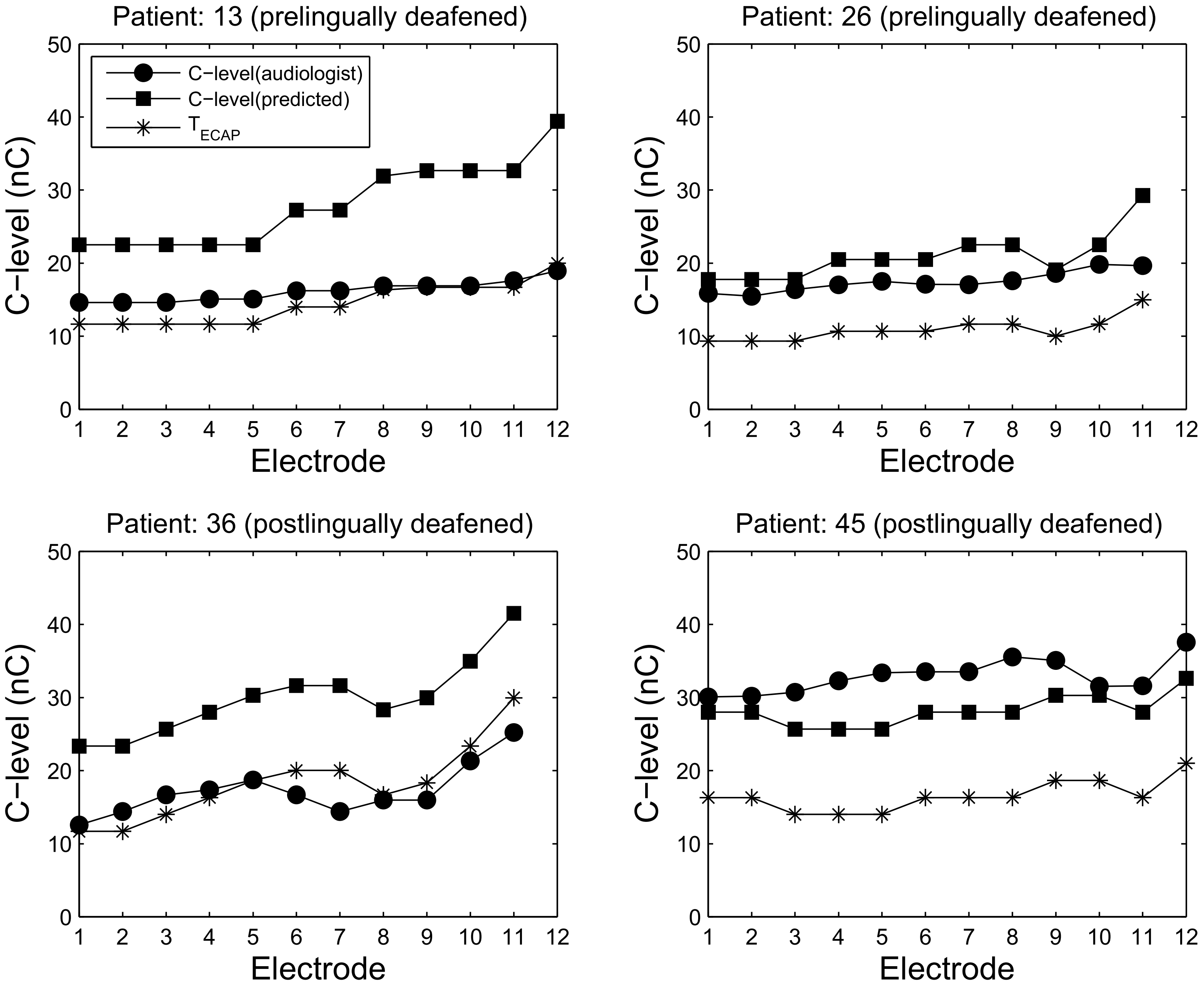


Figure4



Patient: 13 (prelingually deafened)
C−level(audiologist)
C−level(predicted)
T_{ECAP}
C−level (nC)
Electrode
Patient: 26 (prelingually deafened)
C−level (nC)
Electrode
Patient: 36 (postlingually deafened)
C−level (nC)
Electrode
Patient: 45 (postlingually deafened)
C−level (nC)
Electrode

Figure5

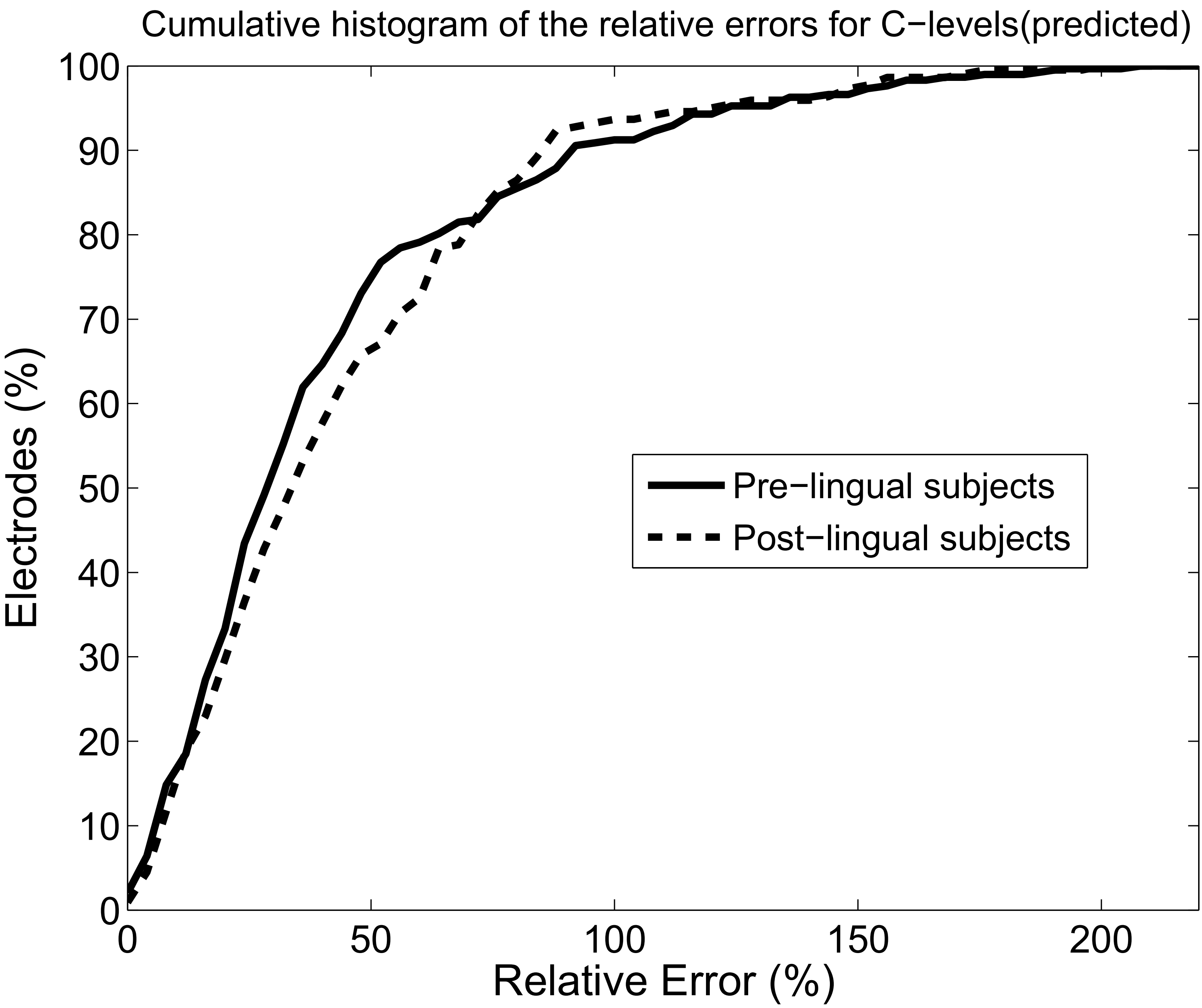

Cumulative histogram of the relative errors for C−levels(predicted)
100
90
80
70
60
50
40
30
20
10
0
Electrodes (%)
0
50
100
150
200
Relative Error (%)
Pre−lingual subjects
Post−lingual subjects

Figure6

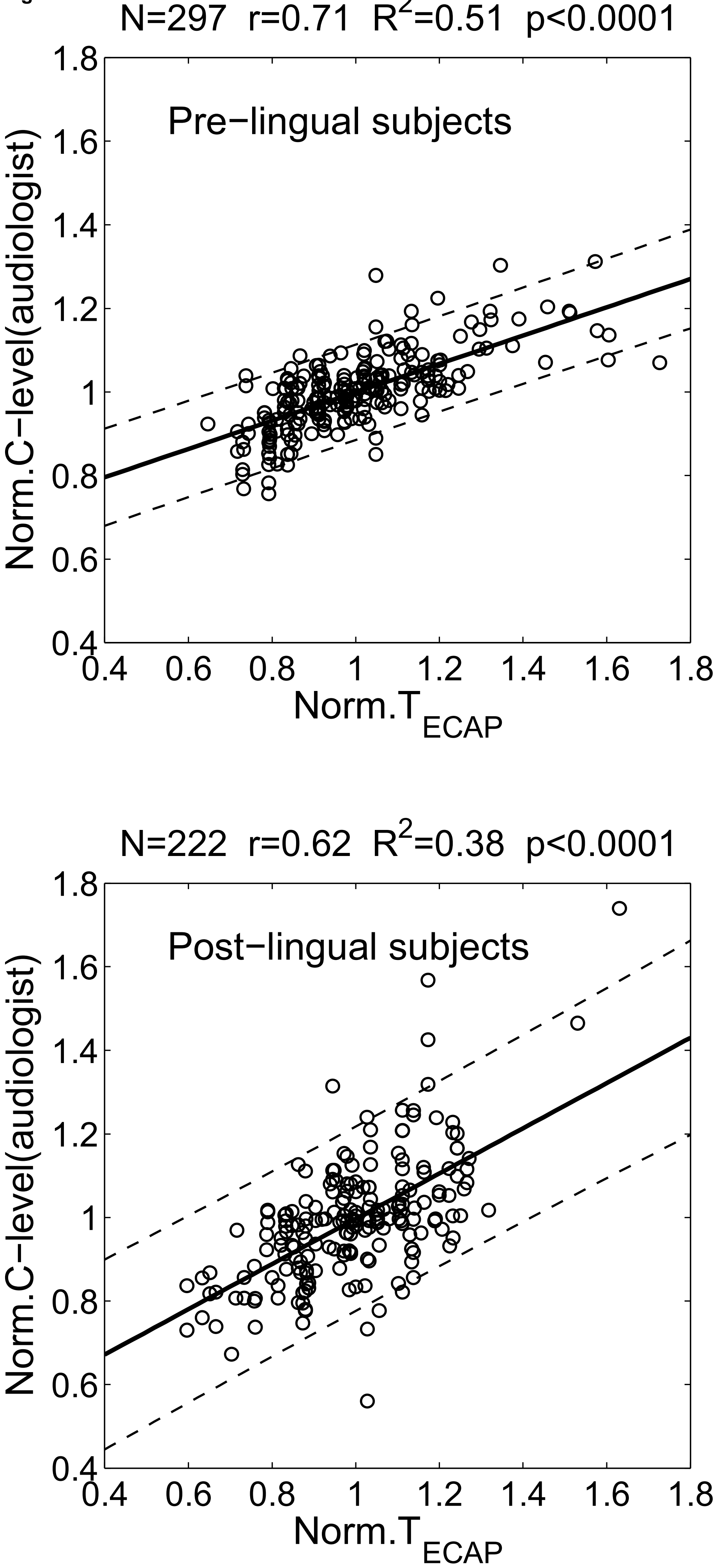

N=297 r=0.71 R2=0.51 p<0.0001
Pre−lingual subjects
Norm.C−level(audiologist)
Norm.TECAP
N=222 r=0.62 R2=0.38 p<0.0001
Post−lingual subjects
Norm.C−level(audiologist)
Norm.TECAP

Figure7

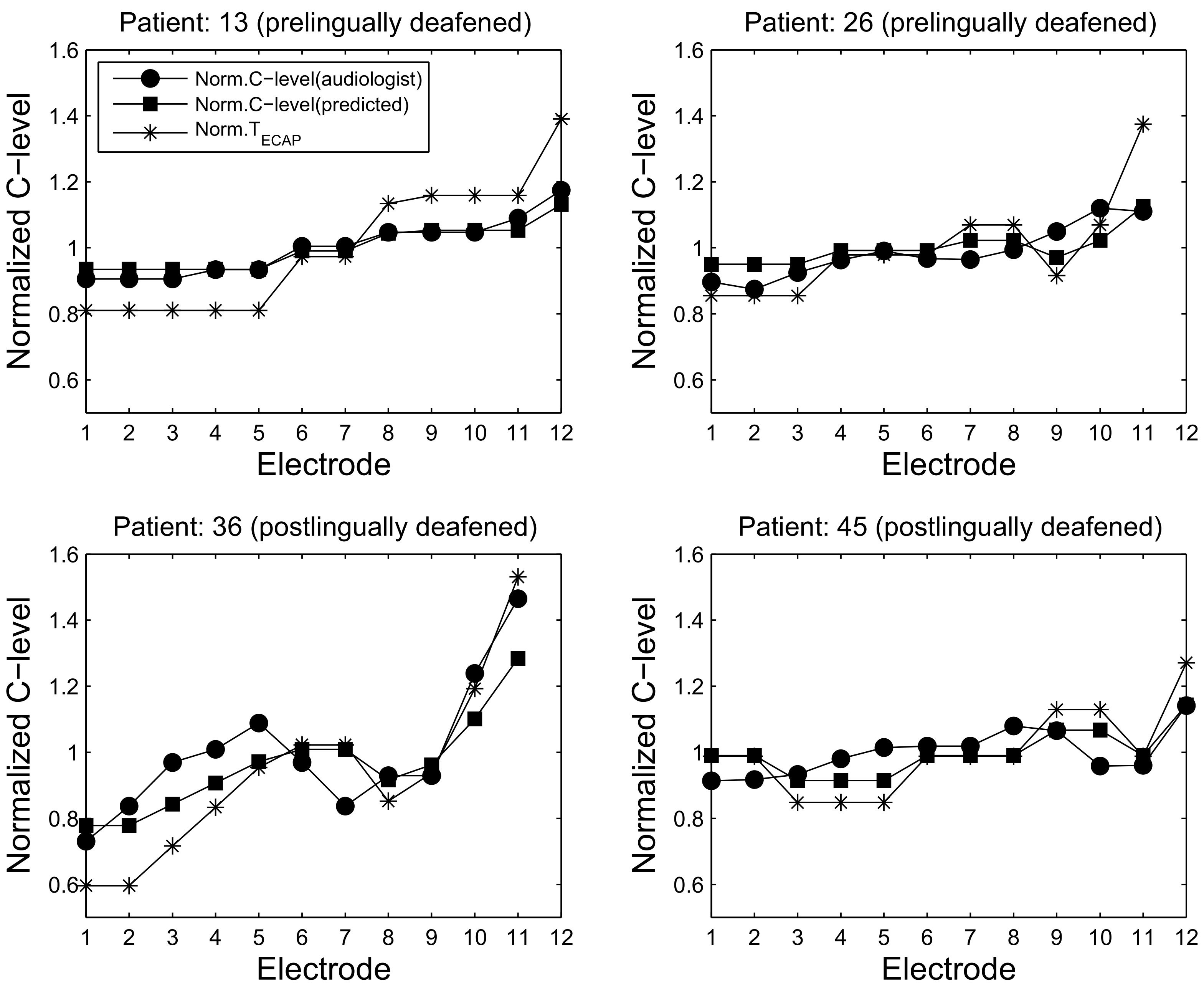
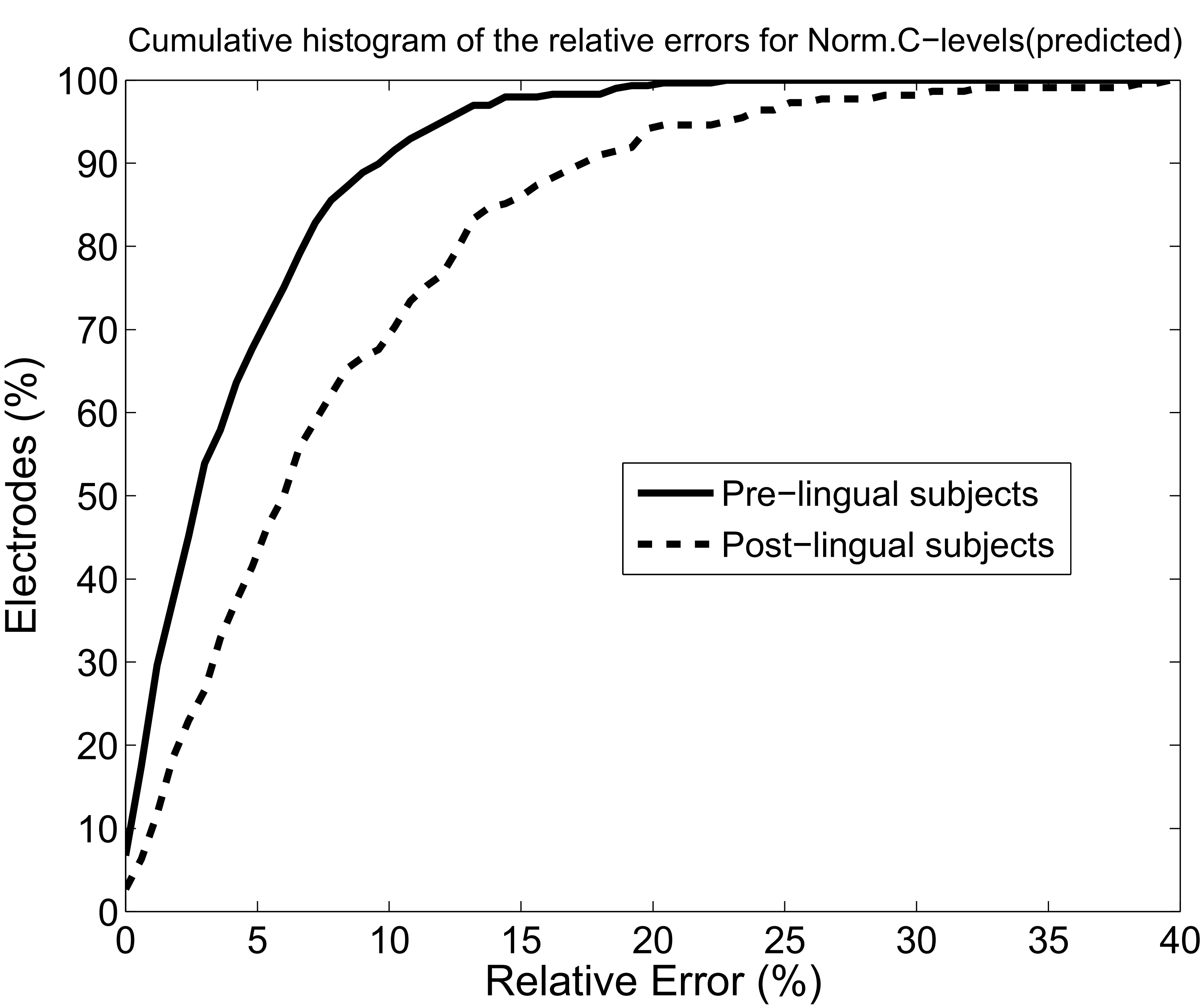

Patient: 13 (prelingually deafened)
Patient: 26 (prelingually deafened)
Patient: 36 (postlingually deafened)
Patient: 45 (postlingually deafened)
Norm.C−level(audiologist)
Norm.C−level(predicted)
Norm.T$_{ECAP}$
Normalized C−level
Electrode
1.6
1.4
1.2
1
0.8
0.6
1 2 3 4 5 6 7 8 9 10 11 12

Figure8



Cumulative histogram of the relative errors for Norm.C−levels(predicted)
Electrodes (%)
Relative Error (%)
Pre−lingual subjects
Post−lingual subjects
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35
40

Table

Id	Sex	Active electrodes	Age at ECAP testing (yrs)	Time from first fitting (mnths)	Age of deafness
1	M	9	1.46	3	Prelingual
2	F	11	2.03	12	Prelingual
3	F	10	2.28	14	Prelingual
4	M	12	2.57	14	Prelingual
5	F	12	2.68	6	Prelingual
6	F	11	2.84	3	Prelingual
7	F	12	3.26	15	Prelingual
8	M	9	3.39	21	Prelingual
9	M	8	3.62	18	Prelingual
10	M	11	3.93	4	Prelingual
11	M	11	3.98	12	Prelingual
12	F	12	4.91	41	Prelingual
13	F	12	5.09	25	Prelingual
14	F	9	5.17	24	Prelingual
15	F	11	5.21	20	Prelingual
16	F	10	5.27	6	Postlingual
17	M	11	5.46	3	Prelingual
18	M	11	5.48	6	Postlingual
19	M	12	5.60	33	Prelingual
20	M	11	5.75	37	Prelingual
21	M	10	5.97	41	Prelingual
22	F	11	6.46	8	Prelingual
23	M	9	6.55	42	Prelingual
24	F	12	6.58	23	Prelingual
25	F	12	6.62	60	Prelingual
26	F	12	6.85	10	Prelingual
27	M	10	7.92	14	Postlingual
28	M	12	8.05	3	Postlingual
29	F	12	8.49	3	Prelingual
30	M	12	8.56	9	Postlingual
31	F	11	9.17	24	Postlingual
32	M	12	9.82	20	Prelingual
33	F	10	11.53	39	Postlingual
34	M	12	11.55	21	Postlingual
35	F	8	11.67	36	Prelingual
36	F	11	13.42	33	Postlingual
37	M	9	14.31	39	Prelingual
38	M	10	17.51	36	Postlingual
39	M	10	19.30	39	Postlingual
40	M	12	19.47	37	Postlingual
41	M	11	25.51	3	Postlingual
42	F	10	25.60	37	Postlingual
43	M	12	33.59	37	Postlingual
44	M	11	47.26	38	Postlingual
45	F	12	53.48	10	Postlingual
46	M	12	55.19	38	Postlingual
47	M	10	55.96	13	Postlingual
48	M	11	64.57	3	Postlingual
49	M	8	67.85	34	Postlingual

Table 1. Profiles of all subjects in this study.

Electrodes	On	Off	Total
ECAP	519	19	538
NoECAP	10	40	50
Total	529	59	588

Table 2. Number of electrodes activated and deactivated (ON/OFF), presenting and not presenting ECAP response (ECAP/NoECAP).

Subjects	x	y	N	a	SE(a)	b	SE(b)	r	R^2	p	semi-width 95% C.I.
Pre	T_{ECAP}	C-level(audiologist)	297	2.03	0.15	-1.18nC	2.89nC	0.62	0.38	<0.0001	31.56nC
Post	T_{ECAP}	C-level(audiologist)	222	0.99	0.13	11.76nC	2.59nC	0.47	0.22	<0.0001	27.35nC
All	T_{ECAP}	C-level(audiologist)	519	1.48	0.10	6.16nC	2.04nC	0.53	0.28	<0.0001	31.21nC
Pre	Norm.T_{ECAP}	Norm.C-level(audiologist)	297	0.34	0.02	0.66	0.02	0.71	0.51	<0.0001	0.11
Post	Norm.T_{ECAP}	Norm.C-level(audiologist)	222	0.54	0.05	0.46	0.05	0.62	0.38	<0.0001	0.22
All	Norm.T_{ECAP}	Norm.C-level(audiologist)	519	0.42	0.02	0.58	0.02	0.63	0.40	<0.0001	0.17

Table 3. Results of the regression analysis for prelingual, postlingual and all patients considered in this study. N represents the number of electrodes, a and b indicate the slope and the y-intercept of the regression line, respectively. SE(a) and SE(b) are the standard errors of a and b, respectively. The parameters r, R^2 and p are the correlation coefficient, the coefficient of determination and the probability associated with the null hypothesis of statistical independence, respectively. The semi-width of the 95% confidence intervals is also shown.

Subjects		N	mean(%)	std(%)	P_{50} (%)	P_{80}(%)	P_{95}(%)
Pre	$RE_{C\text{-level(predicted)}}$	297	42.70	38.59	31.10	63.30	124.80
Post	$RE_{C\text{-level(predicted)}}$	222	45.22	36.33	36.37	70.93	119.86
All	$RE_{C\text{-level(predicted)}}$	519	43.78	37.62	32.28	68.00	124.78
Pre	$RE_{Norm.C\text{-level(predicted)}}$	297	4.24	4.02	3.06	6.84	12.36
Post	$RE_{Norm.C\text{-level(predicted)}}$	222	8.36	8.38	6.54	12.90	23.16
All	$RE_{Norm.C\text{-level(predicted)}}$	519	6.00	6.59	4.08	9.72	18.06

Table 4. Analysis of the relative error of ECAP-based C-levels (upper three rows) and normalized C-levels obtained using the proposed ECAP-based fitting procedure (lower three rows) for pre-lingual, post-lingual and all subjects included in this study. The number N of electrodes, the mean and the standard deviation of the relative error are indicated. P_{50}, P_{80} and P_{95} are the 50^{th}, 80^{th} and 95^{th} percentiles, respectively.

			Without Normalization eq. (6) (7)			With Normalization eq. (11) (12)		
Id	pre/pos	N	MeanRE	MaxRE	$N_{RE>20\%}$	MeanRE	MaxRE	$N_{RE>20\%}$
1	pre	9	13.8	55.3	1	2.8	11.4	0
2	pre	11	50.8	86.5	11	3.4	6.9	0
3	pre	10	52.6	56.0	9	4.1	7.0	0
4	pre	12	42.3	84.5	12	5.9	10.5	0
5	pre	12	11.7	17.0	0	1.9	6.7	0
6	pre	11	107.8	186.8	11	3.7	7.6	0
7	pre	12	17.6	26.2	7	1.6	5.0	0
8	pre	9	25.7	49.2	9	3.4	12.6	0
9	pre	8	21.9	79.4	3	4.7	8.7	0
10	pre	11	29.0	47.6	9	4.6	16.5	0
11	pre	11	20.4	74.5	4	5.9	13.4	0
12	pre	12	26.0	40.9	8	12.3	20.6	1
13	pre	12	72.1	107.9	12	1.6	3.4	0
14	pre	9	126.5	154.8	9	7.5	17.9	0
15	pre	11	19.7	36.9	6	2.1	7.8	0
16	post	10	47.8	55.4	10	6.8	14.7	0
17	pre	11	153.9	206.2	10	3.8	8.0	0
18	post	11	18.5	28.0	3	5.6	12.9	0
19	pre	12	34.8	37.7	12	2.0	6.3	0
20	pre	11	8.7	19.6	0	3.4	12.1	0
21	pre	10	32.2	51.3	10	4.6	12.4	0
22	pre	11	15.4	26.6	4	4.0	8.6	0
23	pre	9	32.7	43.7	9	1.8	9.7	0
24	pre	12	55.5	99.8	12	9.1	22.1	1
25	pre	12	13.7	24.0	2	3.7	10.2	0
26	pre	12	19.7	48.9	4	4.7	9.4	0
27	post	10	74.8	98.7	10	7.4	14.7	0
28	post	12	149.7	201.3	11	6.8	20.1	1
29	pre	12	65.7	97.8	12	3.1	6.9	0
30	post	12	64.9	173.4	9	25.0	81.0	4
31	post	11	17.2	25.6	5	5.8	10.3	0
32	pre	12	75.2	107.3	12	5.3	12.4	0
33	post	10	29.3	37.5	10	3.6	7.9	0
34	post	12	29.8	49.4	9	13.1	26.3	2
35	pre	8	23.5	49.2	4	2.7	8.3	0
36	post	11	75.3	119.9	11	9.2	20.1	1
37	pre	9	29.0	41.4	9	5.0	11.6	0
38	post	10	36.0	59.4	8	8.8	23.6	1
39	post	10	49.8	57.5	10	11.0	24.8	1
40	post	12	72.8	95.4	12	4.5	12.6	0
41	post	11	29.6	43.3	9	6.1	17.3	0
42	post	10	38.9	45.3	10	5.6	20.2	1
43	post	12	16.1	28.7	3	9.7	28.9	1
44	post	11	23.1	62.3	4	12.5	32.0	2
45	post	12	14.2	23.1	3	5.2	11.2	0
46	post	12	17.6	36.8	6	12.0	18.9	0
47	post	10	7.5	13.0	0	4.0	7.1	0
48	post	11	76.8	92.1	11	5.9	23.1	1
49	post	8	62.0	73.6	8	3.9	10.3	0
Pre	Mean		42.8	69.9	7.5	4.2	10.5	0.1
	Stdev		36.1	48.2	4.0	2.4	4.5	0.3
	95thpercent		125.9	187.5	12.0	9.1	20.5	1.0
Post	Mean		45.3	67.6	7.7	8.2	20.9	0.7
	Stdev		33.2	48.8	3.4	4.8	15.4	1.0
	95thpercent		77.1	172.8	11.0	13.1	31.9	2.0
All	Mean		43.9	68.9	7.6	5.9	14.9	0.3
	Stdev		34.5	48.0	3.7	4.1	11.7	0.8
	95thpercent		125.9	187.5	12.0	12.4	28.6	2.0

Table 5. Individual subject analysis of the error associated with the ECAP-based C-levels (left column) and with the C-level profiles predicted by the proposed ECAP-based fitting procedure (right column). N represents the number of active electrodes. The mean and maximum relative error and the number of electrodes with an error higher than 20% are shown. The mean, the standard deviation and the 95th percentile for pre-lingual, post-lingual and all subjects are also indicated.