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Chapter 5

Threshold levels of dual electrode stimulation in cochlear implants

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Abstract

Simultaneous stimulation on two contacts (current steering) creates intermediate pitches between the physical contacts in cochlear implants. All recent studies on current steering have focused on Most Comfortable Loudness levels and not at low stimulation levels. This study investigates the efficacy of dual electrode stimulation at lower levels, thereby focusing on the requirements to correct for threshold variations.

With a current steered signal, Threshold Levels were determined on 4 different electrode pairs for 7 different current steering coefficients (α). This was done psychophysically in twelve postlingually deafened cochlear implant (HiRes90K, HiFocus1J) users and, in a computer model, which made use of three different neural morphologies.

The analysis on the psychophysical data taking all subjects into account showed that in all conditions there was no significant difference between the Threshold Level of the physical contacts and the intermediate created percepts, eliminating the need for current corrections at these very low levels. The model data showed unexpected drops in threshold in the middle of the two physical contacts (both contacts equal current). Results consistent with this prediction were obtained for a subset of 5 subjects for the apical pair with wider spacing (2.2 mm). Further analysis showed that this decrease was only observed in subjects with a long duration of deafness.

For current steering on adjacent contacts the results from the psychophysical experiments were in line with the results from computational modelling. However, the dip in the threshold profile could only be replicated in the computational model with surviving peripheral processes without an unmyelinated terminal. On the basis of this result, we put forward that the majority of the surviving spiral ganglion cells in the cochlea in humans with a long duration of deafness still retain peripheral processes, but have lost their unmyelinated terminals.

Introduction

Cochlear implants (CIs) are widely used as treatment for profoundly hearing impaired children and adults. The main goal of a CI is to recover a perception of sound and, in particular, speech information. However, implanted adults and children are still experiencing problems in challenging listening situations, such as background noise or listening to music. One reason for this might be reduced spectral resolution caused by the limited number of physical electrodes in the array (Brendel et al. 2009; Hughes and Goulson 2011). Dual electrode stimulation (DES), either simultaneous (Donaldson et al. 2005; Townshend et al. 1987) or sequential (Kwon and van den Honert 2006; McDermott and McKay 1994), has been proposed as a method to increase the number of perceivable pitches with CIs. In simultaneous DES (also called current steering), the summation of two electrical fields produces excitation of nerve fibers intermediate to the stimulated contacts. Therefore it can lead to generation of additional pitch percepts beyond those generated by stimulation of a single contact. The percept is controlled by a current steering coefficient α. This coefficient is defined as the fraction of the total current delivered through the more basal contact of the pair. Therefore, $\alpha = 0$ denotes stimulation of the apical contact only and $\alpha = 1$ pure stimulation of the basal one. The number of intermediate percepts thus created along the whole array varies among CII/HiRes 90K implant users (ranging from 8 – 466 percepts) and between studies (the average ranging from 20-93 percepts) (Firszt et al. 2007; Koch et al. 2007; Snel-Bongers et al. 2012).

The perceived pitch depends on the neural excitation pattern induced by the DES. Frijns et al. (2009b) examined the neural excitation pattern for both simultaneous and sequential DES, both psychophysically and using computational modeling. For current levels close to Most Comfortable Loudness level (MCL), they found that the excitation area moves smoothly between the contacts as a function of α producing an almost constant loudness (Figure 1C and D). However, the computational model also showed that, in some situations, there was discontinuous stimulation for the different α-values, especially at the lowest stimulation levels (Figure 1A and B). Similar effects were found while evaluating DES in animals using neural recordings (Bonham and Litvak 2008). Consequently, the centre of excitation jumped from one electrode contact region to the other. Both our model and the physiological studies suggest that at a constant stimulation level the number of activated neurons changes for different α-values. To stimulate at Threshold Level (TL) for various α-values then requires a current level correction during DES.

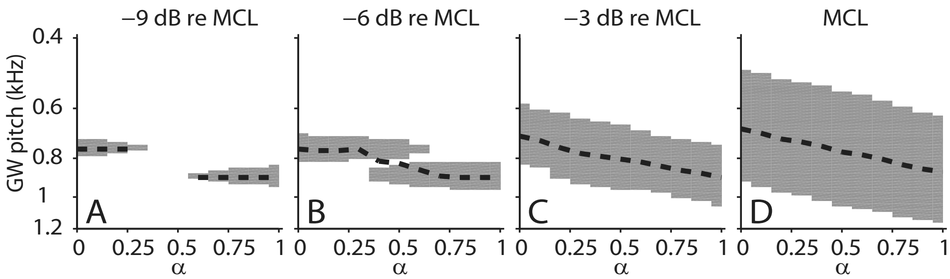

Figure 1. *Current steering plots for AS contacts in a HiFocus 1 electrode (outer wall position) calculated by Frijns et al. (2009b). The nerve fibers exhibit a peripheral process without an unmyelinated terminal (UT). The ordinate axis denotes the associated place pitch of the fibers according to the Greenwood (GW) map. The excitation area is shaded grey and its center is indicated by a dashed line. Panes from left to right show results for stimulation levels from near threshold (-9 dB re MCL) to MCL.*

The human cochlea model developed at Leiden University Medical Center has been used to evaluate effects of intra-cochlear position (Frijns et al. 2001), neural degeneration (Briaire and Frijns 2006) and effects of multipolar stimulation (Frijns et al. 2011) on thresholds and spread of excitation. The realistic tapering structure of the cochlear model allows for the evaluation of excitation differences between the base and the apex of the cochlea. In the model, TL has been shown to depend on variables such as the position of the electrode contacts in the scala tympani (i.e. lateral or peri-modiolar positions) and the presence or degeneration of the peripheral axonal processes. The model consists of two parts, a volume conduction part simulating the current flow through an implanted cochlea and a neural part simulating the response of the nerve fibers (Briaire and Frijns 2000; Briaire and Frijns 2005; Briaire and Frijns 2006; Frijns et al. 2001; Frijns et al. 2009a; Frijns et al. 2009b). In the present study this model will be used to evaluate the behavior of the threshold under different current steering conditions.

All recent studies on current steering have focused on MCL level and not on TL. When current steering is used in speech coding strategies, it is of interest to know what happens at TL. Firstly, because sounds are presented at levels ranging from threshold to MCL level and not only at MCL level. If large corrections were needed then if, for example, one bit of the frequency spectrum were dominated by a component whose frequency caused it to be sent entirely to one electrode, and another region had a frequency content that led to current sharing, this could distort the representation of the frequency spectrum. In addition, TL is part of the clinical fitting procedure. At MCL, a current correction is needed to maintain constant loudness for non-simultaneous DES on adjacent electrodes, while it is not for most simultaneous DES (Donaldson et al. 2005; Frijns et al. 2009b; Snel-Bongers et al. 2011; Snel-Bongers et al. 2012). Based on the findings with our computational model described above (Figure 1A, 1B), it was hypothesized that such a current correction is also needed when current steering is employed close to TL. This was evaluated in the present study by computational modeling and with a psychophysical experiment. Experiments were conducted at two locations along the cochlea (apical and basal), for two adjacent contacts and for two non-adjacent contacts with one electrode in between (Snel-Bongers et al. 2011).

Method

Subjects

12 postlingually deafened adults implanted at LUMC in 2007 with a HiRes 90K HiFocus-1J^{TM} cochlear implant (Advanced Bionics, Sylmar, CA) took part. All subjects had at least one year experience with their implant and a phoneme score of at least 70%, measured at 65 dB SPL with the standard Dutch monosyllabic word speech test (Bosman and Smoorenburg 1995). Specific subject information is provided in Table 1. The study was approved by the Leiden University Medical Center Ethics Committee under number P02.106.L. Written informed consent was obtained from the participants.

Assessment of electrode position

The position of the electrode array and, thereby, the electrode contacts, was determined from post-operative CT-scans which are a routine part of the clinical CI program. To measure the exact position of the electrode contacts, a multiplanar reconstruction (MPR) was made (Verbist et al. 2005). A system of coordinates, according to an international consensus (Verbist et al. 2010), was entered in the postoperative MPR, using a custom Matlab application (MathWorks, Natick, MA) as described in a previous paper (Snel-Bongers et al. 2011). All electrode contacts were marked by an experienced physician. In line with the consensus, the angles used in this study were calculated with the round window as the 0º reference.

Table 1. *Subject demographics.*

	Gender	Age (years)	Aetiology	Duration of deafness (years)	CI side	CI usage (months)	CVC Ph%	Electrodes tested 180°	360°
S1	Male	64	Otosclerosis	23	right	23	89	11	4
S2	Female	69	Meningitis	36	right	52	81	11	5
S3	Male	60	Medication	4	left	52	92	13	6
S4	Female	57	Unknown	27	right	44	83	11	3
S5	Female	58	Unknown	42	right	33	87	9	2
S6	Female	77	M. Meniére	12	right	52	72	11	5
S7	Male	55	loudness	4	right	61	84	13	6
S8	Female	44	Unknown	36	right	20	92	11	5
S9	Male	71	Familiar progressive	26	left	29	84	11	4
S10	Male	50	Otosclerosis	6	left	38	96	12	4
S11	Female	72	Familiar progressive	30	right	37	86	11	4
S12	Male	53	Unknown	43	left	32	89	9	2
Average		61		24		39	86		

Speech perception scores are given as percentage phonemes correct (Ph%) in phonetically balanced monosyllabic (CVC) words.

For each subject the electrode contact closest to 360º (apical site, AS) and the one closest to 180º (basal site, BS) were selected on the electrode array (Table 1). Current steering was applied between the contact at the reference angles e (360º and 180º), and the two contacts in the basal direction (e+1 and e+2), creating two pairs with a spacing of one and two contacts (1.1 mm and 2.2 mm) respectively. Throughout this paper the pairs consisting of electrode contacts (e and e+1) and (e and e+2), will be referred to as 'pair e+1' and 'pair e+2' respectively.

The CT-scan was further used to determine the distance from the electrode contacts to the medial wall of the cochlea. After locating each electrode contact individually, a line was generated from the contact to the center of the modiolus. After identifying the location of the medial wall, the distance was calculated along this line (Snel-Bongers et al. 2012).

Computer model

For the modeling part of this study, a computational model of the implanted human cochlea, which has been developed over the years at Leiden University Medical Center, was used (Briaire and Frijns 2005; Frijns et al. 2001; Frijns et al. 2011; Frijns et al. 2009a). The first part of the model consists of a volume-conduction model that calculates electrical potentials at the auditory nerve fibers located in a realistic three-dimensional representation of a human cochlea implanted with a geometrically accurate representation of the HiFocus electrode array (Advanced Bionics, Sylmar, CA, USA). Secondly, an active nerve fiber model simulates neural responses to specific stimulation patterns produced by the cochlear implant, using the calculated potentials at the location of the nodes of Ranvier of the primary auditory nerve fibers. Neural excitation profiles were generated at the same electrode locations and with the same stimulus configurations as investigated in the subject group, except that the current steering parameter (α) ranged from 0 to 1 in increments of 0.1. Three sets of 320 nerve fibers with different stages of degeneration were created, based on the morphology with an unmyelinated cell body as described in Briaire and Frijns (2005). The first set contained intact neurons with an unmyelinated terminal (UT) added at the tip of the peripheral process (Figure 2). Based on earlier research the length of this UT was set to 10 µm (Liberman and Oliver 1984; Parkins and Colombo 1987). Previous research (Kujawa and Liberman 2009; Lin et al. 2011) demonstrated that the UT is the first part that degenerates after acoustic overexposure with moderate hearing loss as a consequence. The second set therefore, simulates an initial stage of degeneration with peripheral processes, but now without an UT, replacing it by a 1 µm node. The third set consisted of neurons in a further stage of degeneration, without peripheral processes but with their cell bodies and central axons still intact (Briaire and Frijns 2006). The undegenerated peripheral processes followed non-radial trajectories based on data from Stakhovskaya et al. (2007) as described in Frijns et al. (2009b).

From the excitation profiles it was possible to determine how the width of the excitation area depends on the stimulus level. This excitation width is expressed as the length spanned by the tips of the peripheral processes, in other words, the equivalent length along the basilar membrane that corresponds to the neural activation. Based on this loudness definition equivalent loudness was considered to be the equivalent width of excitation in mm along the basilar membrane. Current levels were determined for total basilar membrane excitation lengths ranging from 0 mm (i.e. absolute threshold) to 4 mm. The value of 4 mm excitation was

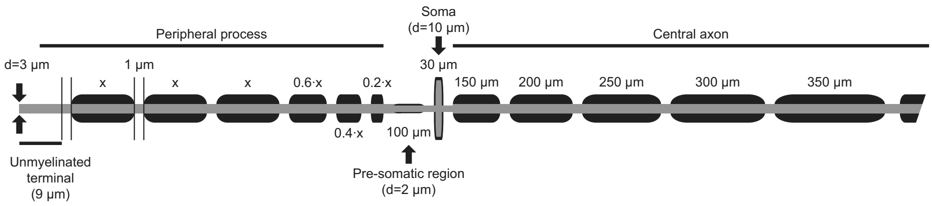

Figure 2. *Representation of the nerve fiber morphology. The peripheral process consists of six scalable segments to adjust for the variable length from the organ of Corti to the cell body, with the unmyelinated terminal (UT) at the end.*

considered to correspond to maximum comfortable loudness (Briaire and Frijns 2006). Throughout the manuscript two definitions for TL were defined: the minimum amount of current needed to excite at least one fiber ("0 mm width") (Briaire and Frijns 2006) called 1st fiber threshold (TL_{0mm}) and a model equivalent of the perceptual threshold (TL_{1mm}) where 1 mm of the length along the basilar membrane is excited.

Psychophysical experiment

The main outcome for this experiment was the TL_{Φ}, when the signal was just heard, at various values of the current steering coefficient α. The experiment was performed using the Bionic Ear Data Collection System (BEDCS, Advanced Bionics, USA) for the stimulation configuration and using the PsychoACoustic Test Suite (PACTS, Advanced Bionics, Belgium) for the psychoacoustic tests. Stimuli were 300 ms bursts of symmetric biphasic pulses with phase duration of 32 µs and 1400 pulses per second. The inter-stimulus interval was 500 msec. Dual electrode stimuli were always simultaneous.

Rough TLs and most comfortable loudness levels were first determined for each of the six pre-selected electrode contacts individually. The subject was asked to indicate when the signal was just heard (rough TL) and also when the signal sounded most comfortably loud (MCL).

A single run of a 2-Alternative-Forced-Choice, 1-up/2-down adaptive procedure was used to determine TL_{Φ} (Levitt 1971) for each α = 0, 0.17, 0.33, 0.50, 0.67, 0.83, or 1 for all four electrode pairs. The target stimulus consisted of a dual-electrode stimulus at a current level between MCL and TL. The reference stimulus was 0 mA. Within each trial, the two stimuli were presented in a random order. The subject was required to select the stimulus that generated a sound percept. A response was considered to be correct when the subject chose the target stimulus. The current level of the target stimulus was decreased until the subject chose the wrong interval because no sound was heard for either stimulus. The procedure covered ten reversals (i.e. changes in the direction of the signal level), where the test outcome was calculated over the last six reversals. The current level was altered in steps of 15% increments or decrements for the first four reversals and in steps of 7% for the remaining six. If a downward or upward trend was detected over the last six reversal points by the program (PACTS), determined using an algebraic algorithm (website, 2009), then the test was extended, assuming that either the adaptive procedure had not yet converged to the subject's discrimination limit or that the measurement was unreliable due to the behavioral status of the subject, for example loss of attention (Snel-Bongers et al. 2011).

To correct for the variation in the absolute thresholds between all subjects and the four stimulated positions, the data were normalized. TL for each α was normalized on both ends ($\alpha = 0$ (TL_0) and $\alpha = 1$ (TL_1)) with linear interpolation in between, using the following formula:

$$TL_{normalized} = TL_{\alpha} / (TL_0 + \alpha\,(TL_1 - TL_0)) \qquad \text{(Eq.1)},$$

where TL_{α} is the TL for that specific α ($0 \le \alpha \le 1$).

As a consequence, all threshold corrections are calculated relative to $TL_{normalized}$, and do not reflect the absolute current level.

Statistical analysis

For the threshold detection experiments a linear mixed model analysis (Fitzmaurice et al. 2004) was performed on the normalized data. A linear mixed model can take several data points from one subject into account, and gives an overview of the interaction of all these data with the main values, the comparison of all data with one data point and corrects for the individual subject (Snel-Bongers et al. 2012). Further, the linear mixed model corrects for missing data. A Bonferroni correction was applied to all statistical tests, to correct for the fact that (up to five) different tests were performed on the same data, resulting in a significance criterion of $p<0.01$.

All data were analyzed using the SPSS 17 (Statistical Package for the Social Sciences, SPSS inc., Chicago, IL) statistics software package.

Results

Electrode position

The mean location of the apical and basal electrode sites, measured from the round window, was at 364° (±11°) and 180° (±7°) respectively. The apical electrode contacts were significantly closer ($p = 0.026$) to the medial wall (1.19 mm +/- 0.11) than the basal contacts (1.33 mm +/- 0.12).

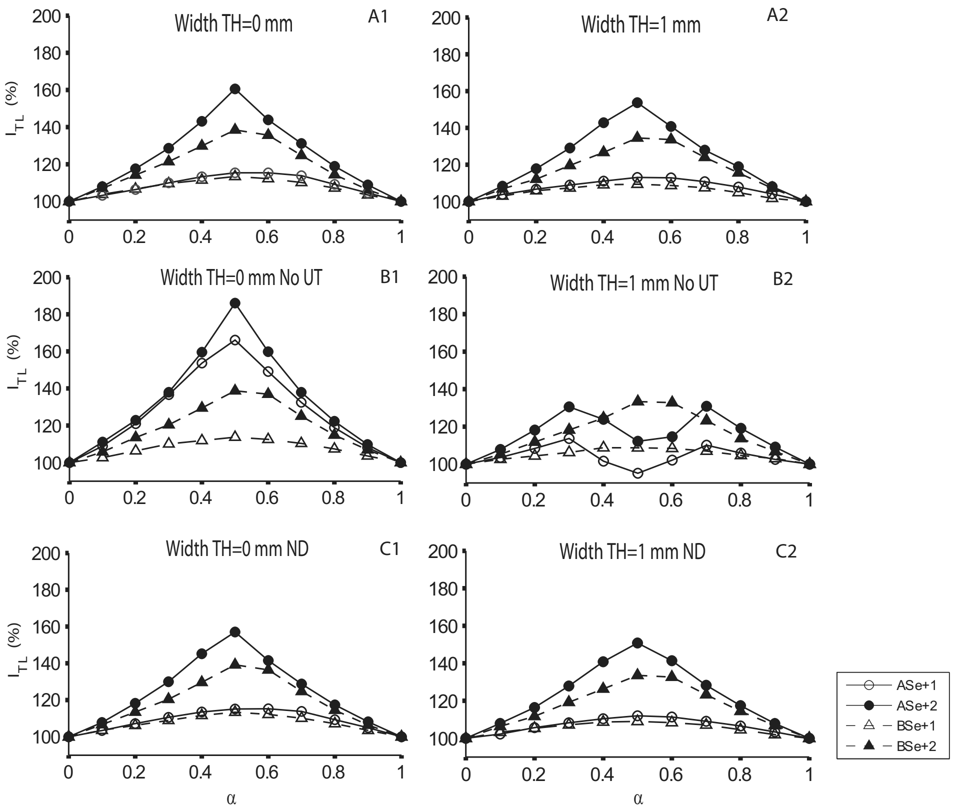

Figure 3. *Computational modeling results of the loudness balancing experiment for the model with a peripheral process with an UT (A), a peripheral process without UT (B) and without peripheral processes (C). The circles represent the data at the AS of the array and the triangles data at the BS of the array, where the open symbols are pair e+1 and the filled symbols pair e+2. The data was normalized on both ends (α = 0 and α = 1) (eq. 1) and the other currents (I_{TL}) are expressed in percentages of this values. Panes on the left show results for excitation lengths of 0 mm and of 1 mm on the right.*

Computer model

Figure 3 shows normalized current levels needed to achieve 0 mm (TL_{0mm}), and 1 mm (TL_{1mm}) excitation along the basilar membrane in a cochlear model with either intact neurons (SG cells with a peripheral process) with an UT (3A), without an UT (3B, No UT) and a degenerated peripheral process (3C, DPP), for current steered and spanning pairs (e+1: open vs. e+2: filled symbols) at AS and BS (AS: triangles vs. BS: circles). Generally speaking, the e+1 pair needs less current correction than the e+2 pair and the apical pair needs more current correction than the basal pair, regardless of the threshold criterion. Further, more current correction is needed in the fiber model without UT in comparison with the other two fiber degeneration states.

In Figure 3B1, it is visible that apically more current correction is needed to reach TL_{0mm} than basally. The curve for e+1 at BS is almost flat, while the others peak more or less around α = 0.5. The basal electrodes have the same pattern for the TL_{1mm} condition (Figure 3B2). However, for the apical sites current levels for 1.0 mm show a clear dip of 60% relative to the TL_{0mm} condition. Interestingly, in the case of the dip, the calculated excitation profiles showed that initial excitation takes place at the peripheral processes, while it occurs in the central axons in most other cases.

This reduced TL around α = 0.5 can also be seen in Figure 1, which was generated with nerve fibers with peripheral processes, but without an UT. From Figure 1A (for stimuli 9 dB below MCL) it is clear there is a dependence of the number of excited fibers on α, even resulting in an absence of excited fibers at the center (α= 0.5). This indicates that the current level needs to be varied (increased) as a function of α if a constant number of excited fibers has to be maintained regardless of α. In figure 1B the situation for a 3 dB higher current level is shown. The center of the excitation now consists of two regions (one around each individual contact). For α = 0.5, both regions co-exist and lead to a higher number of excited nerve fibers (i.e., increased loudness with the same amount of current). As a result, the current to maintain constant loudness over the whole range of α from 0 to 1 shows a minimum at α=0.5.

Figure 3A and 3C show the plots for the other two neural conditions (with UT and without peripheral process, respectively). These plots are not essentially different for the basal pairs. For the apical pairs however for TL_{0mm}, particularly pair e+1, less current correction is needed to reach TL (Figure 3A1 and 3C1) in comparison with the graphs in Figure 3B1. Contrary to Figure 3B2, Figure 3A2 and Figure 3C2 do not show a dip for apical electrode pairs.

For both cases (Figure 3A and 3C), the excitation region will be a single area that shifts gradually between e and e+x. However, the excited region does decrease in size as α approaches 0.5 for low current levels. In line with this, the required stimulus levels are elevated for pair e+1by approximate 10% around α = 0.5 for both TL criteria (first fiber, or on the basis of a distinct width of the excited region). With elevation up to 65%, this effect is larger for pair e+2 than for adjacent electrode contacts.

Psychophysical results

In Figure 4, the individual psychophysical results, normalized on both the apical and basal electrode of the pair (Eq.1), are shown for the two different positions in the cochlea (AS: circles vs. BS: triangles) and both measured electrode pairs (e+1: open vs. e+2: filled symbols). The average results are shown in Figure 5. Linear mixed modeling performed on the data excluding α = 0.0 and α = 1.0 showed that there is no difference between the curves for the four electrode pairs ($F_{(221)}$= 1.822, P = 0.145). The average curves suggest (figure 5) that the pairs e+2 need on average more current,correction like in the computer model (figure 3), but the e+1 (101.29%) and e+2 (104.26%) pairs were not significantly different ($F_{(223)}$= 1.969, P = 0.144) from each other. Also the position in the cochlea had no significant ($F_{(223)}$= 1.969, P = 0.162) effect on TLs (AS: 101.35% and BS: 104.20%), which is in line with the model predictions, which use 1 mm excitation as threshold criterion. No relation was found between TL_{Φ} and the distance to the medial wall ($r^2_{(24)}$ = -0.072, P = 0.737).

Contrary to some of the model predictions, the TL_{Φ} for intermediate values of α are not significantly different ($F_{(265)}$= 0.774, P = 0.569) from the flanking electrodes (α = 0 and α = 1), as demonstrated with the linear mixed model run on all data together. In line with this result, TL_{Φ} found with α = 0.5 on both adjacent (pair e+1) (103.55% on average) and nonadjacent electrode (pair e+2) (100.88% on average) pairs were not significantly different from those of the apical contact ($t_{(22)}$= -1.380, P = 0.182 and ($t_{(23)}$= -1.132, P = 0.269, respectively).

The model outcomes, shown in Figure 3B2, exhibit a dip for α = 0.5 in TL_{1mm} at AS, which is also visible in the psychophysical results for pair e+2 at 360° (Figure 5). A standard Student's T-test showed a decrease of the TL_{Φ} of α = 0.5 (94.33 %) compared with α = 0.33 (104.03 %), but no difference with α = 0.67 (102.87 %) ($F_{(66)}$ = 1.505, P = 0.042, and 0.072 respectively). After application of the Bonferroni correction, these differences did not meet the significance criterion.

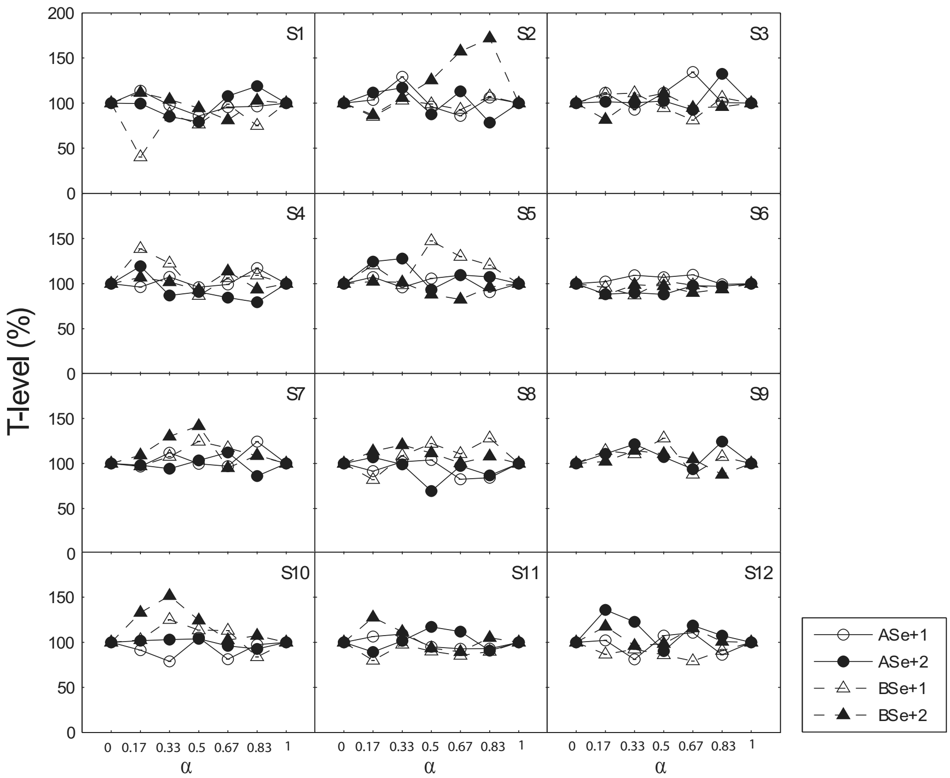

Figure 4. *Individual results for the twelve subjects (S1-12) on the loudness balancing experiment. The circles represent the data of the AS pairs and the triangles the BS pairs, where open symbols are for pair e+1 and filled symbols are for pair e+2. The data were normalized and are expressed in percentages. The different values of α are denoted on the horizontal axis.*

From Figure 4, it is clear that such a dip in AS pair e+2 (at least 10 % lower threshold values at $\alpha = 0.5$ compared to $\alpha = 0.33$ and $\alpha = 0.67$) is visible in the individual results of subjects S1, S2, S5, S8 and S12. To find out, whether these subjects share a common factor, the subjects were divided into two groups, one group with the dip (5 subjects) and a group lacking it (7 subjects). A post-hoc analysis with a standard Student's T-test was performed, using p = 0.01 as the level of significance after correcting according to Bonferroni. The average duration of deafness for the group without a dip (15.5 years) was significantly lower ($t_{(10)}$= 3.599, P = 0.005) than that for the group with a dip (36.0 years), while the parameters age at implantation, electrode distance to the medial wall and the absolute value of TL_{Φ} showed no significant difference between these groups ($t_{(10)}$= -0.956, *P* = 0.364, $t_{(10)}$= -0.778, *P* = 0.456 and $t_{(23)}$= 2.010, *P* = 0.056 respectively). This suggests that the duration of deafness is a possible predictor for the dip.

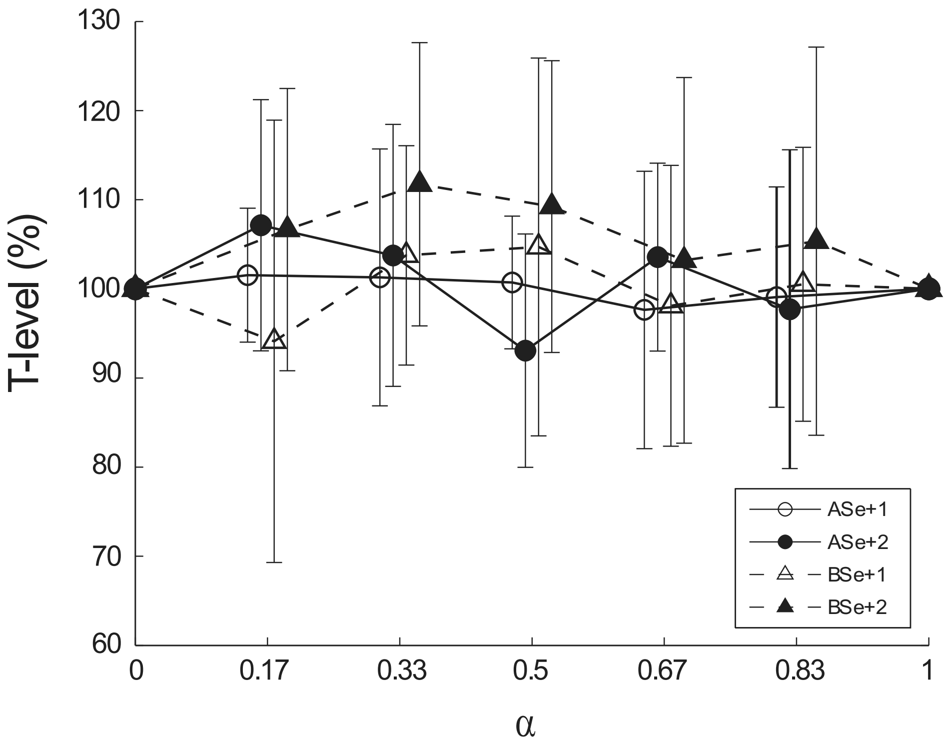

Figure 5. *The average data of the loudness balancing experiment on AS (circles) and BS (triangles) for pair e+1 (open) and pair e+2 (filled). The current was normalized on both ends, where the other percentages are calculated from Eq. 1. The symbols are plotted at staggered α-values along the x axis in order to avoid overlapping of the error bars.*

Discussion

Based on previous computational and physiological results (Bonham and Litvak 2008; Frijns et al. 2009b) it was hypothesized that current steering at TL requires a current correction in order to maintain equal loudness for all current weighting combinations between a pair of electrodes. However, TLs are not significantly influenced by the current steering coefficient, at least for adjacent and nonadjacent electrode pairs up to 2.2 mm wide. For the e+1 electrode pairs model outcomes, using TL_{1mm} as threshold criterion, were comparable to the patient data for the same condition. In the model larger distances between the contacts give rise to the need of current correction, which was not observed in the subjects.

The model showed a dip in the amount of current correction at $\alpha = 0.5$, specifically for the apical contacts, and only in the condition where the UT was degenerated but the rest of the fiber was still intact (Figure 3B2). This same effect was observed in some of the subject specific outcomes at the same location, although the effect was not large enough to reach a significant level in the whole group. With post-hoc analysis with the dip as group factor, the duration of deafness was the only parameter which showed a significant correlation with the presence of this decrease in threshold at $\alpha = 0.5$. The group with the dip had the longest mean duration of deafness (15.5 yr vs. 36.0 yr).

This observation can shed some light on the possible time course of neural degeneration in humans. The UT could be the first structure that degenerates after several years of deafness. This would imply that the majority of SG cells in subjects with a long duration of deafness still have their peripheral processes, although the UT is degenerated. In line with this hypothesis, and contrary to earlier reports (Nadol and Eddington 2006; Sly et al. 2007), Rask-Andersen et al. (2010) found that both peripheral processes and SG cells are well preserved in the apical region of the cochlea even after 28 years duration of deafness. At the same time the evidence is growing that the first part that degenerates is the UT, even before the hair cells and the nerve fiber (Kujawa and Liberman 2009; Lin et al. 2011).

As stated above, the model showed only a dip when using the fibers with intact peripheral processes without an UT, while simulations either without peripheral processes or with intact peripheral processes with UT did not exhibit such a dip. The physiological mechanism underlying this fact can be understood as follows: The UT is the unmyelinated connection between the nerve fiber and the hair cell and therefore is likely to behave as a large node of Ranvier. As a consequence, the UT is expected to possess a large electrical capacitance, which must be loaded with the intra neural potential before the fiber can fire in the peripheral process. In this case, the action potential threshold is more easily initiated in the central axon than at the peripheral process, as it must also be in cases of degeneration of the entire peripheral process. Without a UT the action potentials will be initiated in the peripheral process, as a consequence of its reduced thresholds. Additional simulations (data not shown) demonstrated that even partial preservation of peripheral processes suffices to produce this dip. The differences with respect to the location within the cochlea can be understood from the excitation site along the nerve fiber. Contacts in the more apical turns of the cochlea excite the fibers in the peripheral process, while contacts in the base directly stimulate the central axon and thus the influence of the UT is minimalized (Briaire and Frijns 2006).

It is likely, that there are other factors, like the cause of deafness, which influence the course of the degenerative process of the auditory nerve. For instance, Teufert et al. (2006) found, that subjects with idiopathic deafness had the highest residual SG cell count, while subjects with bacterial labyrinthitis had the lowest count. Unfortunately, the present group size and the known large variation in aetiology, preclude an analysis of our data along these lines.

Contrary to the model predictions, only two of the five subjects with a dip in pair AS e+2 also exhibited a dip in pair AS e+1. An explanation for this could be that the simulation conditions are extreme situations, where all the fibers exhibit the same morphological situation. The subjects probably have all three degenerative fiber conditions mixed along the cochlear partition, which may mask effects only present in one specific condition.

It is very likely that the threshold detection criterion is a patient specific parameter, which is not only determined by the situation in the cochlea (besides the number and condition of the residual nerve fibers, also tissue growth, electrode position etc.), but also by central effects. Also in the model the width and depth of the dip is influenced by the threshold criterion. As shown in Figure 3B, with TL_{0mm} the dip is completely absent, while the model predicts a much shallower dip in e+2 and an almost absent dip for e+1 if a value of 0.7mm (rather than 1mm) along the basilar membrane is used as threshold criterion (data not shown). It should be noted that the absolute value of the threshold criterion depends on the spread of excitation in the model, which, in turn, depends on various model parameters.

As stated above, both the model and the psychophysics did not show evidence for the need of current correction to maintain equal loudness for pair e+1. However, for pair e+2 the model showed a clear need for current correction at $\alpha = 0.5$, which was not seen in the psychophysical data. This discrepancy might well be caused by an underestimation of the spread of excitation (SOE) in the model. The narrower the SOE, the higher the need for current correction (Frijns et al. 2009b). The SOE in the model is not only influenced by the TL criterion (figure 3) but also by the (absence of) stochastic neural behaviour and the spatial distribution of the cell bodies in the SG.

Unfortunately, published literature cannot provide much additional evidence, as this is the first clinical study on current steering at threshold, while all other ones have been performed at MCL. Donaldson et al. (2005) showed that for most of the subjects no current correction was needed for creating the same loudness for e (monopolar stimulation) and e+1 with $\alpha = 0.5$. This finding was confirmed by a previous study from our group (Snel-Bongers et al. 2011), but it was demonstrated that higher current levels were required to reach MCL levels for e+x up to an excitation width of 4.4 mm (e+4).

We conclude that with present electrode arrays simultaneous dual electrode stimulation is possible at low current levels and that no current adjustment is necessary to compensate for loudness variations in most cases. The observations for apical contacts in patients with a long duration of deafness are consistent with the model predictions regarding loss of UTs. Therefore, we hypothesize that the majority of the surviving spiral ganglion cells in the cochlea in humans with a long duration of deafness still retain peripheral processes, but have lost their UTs.

In addition, these outcomes are consistent with the notion that psychophysical thresholds are not reached at excitation of the first fiber, but of a region of nerve fibers of approximately 1 mm along the basilar membrane.

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