Dual electrode stimulation in cochlear implants : from concept to clinical application

Snel-Bongers, J.

Author: Snel-Bongers, Jorien
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Chapter 7

General discussion and concluding remarks

Dual electrode stimulation (DES) is a method that is used to encode the spectral fine structure, by enhancing the number of perceived pitches beyond the number of physical contacts. If DES indeed can be used to improve tonotopical resolution, this could result in improved speech perception in general and possibly in improved speech perception in noise and better music perception. This thesis firstly investigates the fundamental principles underlying current steering and phantom stimulation with respect to loudness variation, number of perceived percepts and the spread of excitation. These evaluations were made using psychophysics and computational modeling of the implanted cochlea. Finally, in the last study these fundamental findings are verified by implementing spanning in a speech coding strategy. In a group of test subjects it was shown that spanning can preserve the speech perception scores in patients with defective electrodes.

Loudness

When using DES in a speech coding strategy, the patient must be able to hear the signal. The loudness of a Single Electrode Stimulation (SES) signal depends on the amount of current given on a single electrode contact. With DES the current normally used on one electrode is now divided over two electrodes. When simultaneous DES is applied on adjacent electrode contacts with 1.1 mm spacing at the Most Comfortable Loudness (MCL) level, very little adjustment of that current level is needed to maintain equal loudness in comparison with SES (Chapter 4) (Donaldson et al. 2005), due to electric field summation (Frijns et al. 2009b). Also when stimulating on low stimulation levels (TL), no correction is needed with current steering (Chapter 5). However, when increasing the spanning distance, a current correction is needed on MCL and TL, presumably due to less overlap between the regions of neural excitation produced by the two stimulating contacts (Chapter 4 and 5). In comparison, also non-simultaneous DES requires a current correction to maintain equal loudness due to attenuation of the electrical field. There is no direct electric field interaction, but only interaction on neural level, which results in two separate regions of excitation (Frijns et al. 2009b).

In chapter 4 the adjustment of the current required to maintain equal loudness for various spanning distances was measured, this relation was used in the study of chapter 6. Unfortunately, individual fitting of the virtual channels in the speech coding strategies was still necessary, because the patients were not content with the loudness after implementing the current correction. Also with phantom stimulation, when two electrode contacts are stimulated with non-equal pulses in opposite-polarity, a current correction is needed when increasing σ (the ratio between amplitudes of the two stimulated contacts) (Chapter 3). Phantom stimulation on low stimulation levels is not even possible. The computational model of the cochlea shows that the initial increase in current needed to achieve 4 mm excitation (considered the equivalent of most comfortable loudness level) is caused by the negative stimulus (see Figure 10, chapter 3, page 82). The negative stimulus is counteracting some of the current spread of the positive stimulus. This makes it more difficult for the electrical current to reach the neurons and overall more current is needed to reach 4 mm excitation.

The required current corrections for spanning and for phantom stimulation when actually used in a speech processors can have for example detrimental consequences for battery life. Increase in current can also lead to overstimulation of other structures in the region of the cochlea, for instance the facial nerve (Frijns et al. 2009a). Also stimulation of auditory nerve fibers in another turn of the cochlea can take place, so called cross-turn stimulation. This can lead to perception of another frequency or distortion of sound. Although none of the patients had complains about these topics in the study of chapter 6, where spanning was implemented in a speech coding strategy, this can become a problem when implementing phantom stimulation in a speech coding strategy, because the current levels are much higher here. However, when this correction is not applied, a subject would not be able to hear the created signal.

Spectral channels

As mentioned above, DES can be used to enhance the number of perceived pitches. With simultaneous DES on adjacent or non-adjacent electrodes these pitches are created intermediate to the stimulated electrode contacts, while with phantom stimulation these pitches are created more apical than the stimulated electrode contacts. The number of created pitches differs per subject and per method. However, if patients are able to discriminate between pitches created with current steering, they are also able to discriminate between pitches created with phantom stimulation (Chapter 3). The amount of pitches decreases when increasing the spanning distance (Chapter 4), which can have a negative influence on performance when spanning is used for instance in future devices to decrease the number of physical contacts in an array. On the other hand, additional signal channels are provided, which is a better solution for patients with a defective contact on their already implanted array than nothing.

At the present time, the principle of DES is implemented commercially in the Advanced Bionics Harmony system, using the HiRes 120 speech coding strategy. Instead of 16 spectral channels generated using the physical electrode contacts, 8 intermediate or virtual channels are available per electrode contact pair, giving a total of 120 different pitches. The number of possibly created intermediate pitches with DES, however, differs per subject and has a positive correlation with their speech perception score with monopolar stimulation (Chapter 2). There are subjects who are not able to distinguish between two contacts, which are up till 4 mm apart from each other (Chapter 4) and there are subjects who are able to distinguish more than 40 extra percepts between adjacent electrode contacts (Firszt et al. 2007; Koch et al. 2007). For subjects who are not able to discriminate available spectral channels, virtual channels will probably not be beneficial when used in a speech processor and potentially even detrimental. It is possible that each patient needs an individual adjustment of his or her HiRes program. For example, the patient who is not able to discriminate between two adjacent contacts will maybe reach his or her highest speech perception scores with 8 different pitches, which will give for example a new HiRes program, denoted as HiRes8, instead of HiRes120. While the patient who can differentiate about 20 percepts, will reach his or her highest speech perception score with 300 different pitches and will get a HiRes300 program. Unfortunately, we have not found a parameter that can predict the number of intermediate pitches (Chapter 2). This means that the just noticeable difference of α (JNDα), which can be used to calculate the number of possible intermediate pitches, must be determined individually, which is time-consuming, after which each HiRes program must be individually adjusted. It would be of interest to investigate whether speech perception scores can be increased when each patient will get their individually adjusted HiRes program with DES based on their JNDα.

Another improvement could be to use an “n of m” strategy in HiRes120. In the current implementation of HiRes 120 the stimulation place of the peaks in the spectrum are positioned more accurately. The channels without a peak in their spectral band are, however, stimulated at the edges of the channel on the slope of the peak of the neighboring channel. These stimulations can lead to larger spread of excitation and lower pitch discrimination. The ‘n of m’ addition would only select the channels with a peak that can be steered to the correct excitation place. This will probably reduce the problem of the high interactions between the spectral channels, because of the close proximity of the stimulation areas.

Place of stimulation

When using DES in a speech coding strategy the place or site of stimulation (X) is of interest. This can either be investigated with a psychophysical experiment or with an objective measurement. The X of current steering for $\alpha = 0.5$ was found exactly between the two stimulating contacts with an eCAP forward-masking curve, an objective measure. X appeared to follow a linear pattern up till 4.4 mm for spanning, investigated with a pitch matching experiment, which is a psychophysical experiment. The X of phantom stimulation was determined psychophysically by comparing it with a current steering signal also in a pitch matching experiment. The maximum pitch shift found for phantom stimulation was about 1 electrode contact spacing in the apical direction.

For future investigation, the question arises whether eCAP forward-masking curves will give the same results for spanning and phantom stimulation as found for current steering. Preliminary data of spanning show promising results, however the initial experiment must be extended in future research for better comparison. For example, with taking several different locations of the recording electrode into account. The recording electrode in the eCap experiments, described in Chapter 2, was always at the same position, 2 electrode contacts closer to apical than the stimulated electrode contact. This can be of influence on the determined place of stimulation (van der Beek et al. 2012). Further, the preliminary data of phantom stimulation were not usable, because the used program was not able to implement the required high current correction. New adjustments of the program will make it hopefully possible to determine X of phantom stimulation in the future objectively.

Computational model

To supplement clinical data, simulations of DES excitation were performed using a computational model of the implanted human cochlea developed at Leiden University Medical Center. The computational 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). As shown in chapter 5, the model can be used to understand and explain the result of the psychophysical experiments. Here three different cochlea models were used based on different stages in the degeneration process. After comparing the clinical data with the predictions of the computational model, a new insight in the neural degeneration process of the auditory nerve became apparent. Patients with a long duration of deafness were best compared with the graphs of nerve fiber, which still exhibited a peripheral process, but no unmyelinated terminal (UT), while patient with a significantly shorter duration of deafness were better compared with the graph where an UT was still present. This observation suggested that degeneration of auditory nerve fibers in humans involves loss of UTs rather than loss of complete peripheral processes.

The predictions made by the model in this thesis were comparable with the results of the clinical experiments. This implicates that the model can be used in future studies, but also that it probably can be used in the future for composing an individual speech coding strategy for each cochlear implant user. Here the CT-scan can be used to create an individual model of the cochlea per subject and place the electrode array in the exact same position as in the patient.

Assessment of electrode position with CT scan

As a new element, we selected the tested electrode contacts based on their location in the cochlea, instead of selecting based on their rank number on the electrode array. The main reasons for this choice were the differences between subjects regarding insertion angle, size of the cochlea and electrode position. To locate the exact position of the electrode array, and thereby the individual electrode contacts, we used postoperative high resolution CT-scans. A system of coordinates (Verbist et al. 2005), was used and the angles were calculated from the round window, the 0° reference, according to an international consensus (Verbist et al. 2010). We prefer this approach since it is a reliable and standardized method and allows comparison of comparable parts of cochleae across subjects and across electrode designs. We recommend using it in all future clinical cochlear implant studies. A detrimental effect is caused by the radiation dose of a high resolution CT-scan, especially when making for each cochlear implant patient a pre- and post-operative CT-scan. Fortunately, it is nowadays possible to make use of low dose temporal bone CT-scanning. Nauer et al. (2011) showed that in a comparable study between low-dose versus standard high-dose CT-scans, that the image quality of the new low-dose protocol remains diagnostic for assessing the middle and inner ear anatomy despite a 3- to 8-fold dose reduction. Also Niu et al. (2012) showed that the radiation dose reduces up till 50%, while maintaining diagnostic image quality. Nevertheless, Nauer et al. (2011) pointed out that the image quality of small structures is critical and may be perceived as insufficient.

Next to this, one upcoming dose-saving technique with a high resolution is the cone beam CT. The cone beam CT offers several advantages over the traditional high resolution CT; namely lower radiation dose, reduced flaring from electrode artifacts and lower cost (Faccioli et al. 2009; Ruivo et al. 2009; Trieger et al. 2011). Although the cone beam CT allows relatively safe evaluation of the electrode in the basal turn, a disadvantage is that it is not really a useful tool with deep insertions (Guldner et al. 2012). Cone Beam CT also did not demonstrate adequate resolution to detect reversal of the electrode contacts or basilar membrane rupture (Cushing et al. 2012).

Future perspectives

In this thesis we have shown how fundamental research can help to successfully implement a speech coding strategy, in this case dual electrode stimulation. Phantom stimulation has only been investigated on fundamental grounds, so the next step should be to implement it in a speech coding strategy. Before phantom stimulation can be implemented, two issues must be considered. First impractically high currents may be required to achieve audibility, and this can have a negative influence on battery life, and lead to overstimulation of other structures in the region of the cochlea or to cross-turn stimulation, which can lead to perception of another frequency or distortion of sound. Also the fact that phantom stimulation is not possible on low current levels, limits its clinical applicability. A solution could be, to only use the phantom channels when the energy of the signal is high enough and omitting the low energy signals, like the “n of m” strategy. Secondly, not every patient will be able to distinguish several percepts, which is comparable with current steering. Fortunately, each patient was able to perceive a pitch percept induced to the apical side of the reference contact. However, the patients involved in the study were good performers with a speech perception score above 70%, which can be of influence on their ability to discriminate an extra percept. Possibly, poor performers will be able to perceive a pitch more to apical, but will be unable to discriminate this percept from a monopolar stimulus on the apical contact.

Next to enhancing the number of pitches with DES to improve speech perception scores, it might be possible to improve these scores by limiting the large current spreads in the cochlea of monopolar stimulation. With less current spread, the population of activated neurons would narrow, which would therefore presumably reduce channel interaction across electrode contacts. This should in theory improve spectral resolution and possibly enhance the number of independent channels. As mentioned in chapter 1, phased array, multipole stimulation, is in theory a method that possibly can reduce current spread. According to Frijns et al. (2011), the excitation profiles, computed with the computational model of the cochlea, were broader for monopolar stimulation than for phased array stimulation. This would mean that speech perception could improve. Of concern are, however the high currents needed to achieve audibility, which was also the case in tripolar stimulation. One of the problems with tripolar stimulation was that the large current amplitudes were not physically achievable due to the compliance limits of the device (Litvak et al. 2007). High current levels could, however, also have negative influence on battery life, lead to overstimulation of surrounding structures or to cross-turn stimulation equal to phantom stimulation. This will only become apparent when phased array will be implemented in a speech coding strategy. Preliminary data from our research group (Vellinga et al., KNO vergadering april 2013), however, show that each patient is able to reach MCL with phased array, which is a positive result.

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