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Research paper

Assessing temporal modulation sensitivity using electrically evoked auditory steady state responses

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ABSTRACT

Temporal cues are important for cochlear implant (CI) users when listening to speech. Users with greater sensitivity to temporal modulations show better speech recognition and modifications to stimulation parameters based on modulation sensitivity have resulted in improved speech understanding. Behavioural measures of temporal sensitivity require cooperative participants and a large amount of time. These limitations have motivated the desire for an objective measure with which to appraise temporal sensitivity for CI users.

Electrically evoked auditory steady state responses (EASSRs) are neural responses to periodic electrical stimulation that have been used to predict threshold (T) levels. In this study we evaluate the use of EASSRs as a tool for assessing temporal modulation sensitivity.

Modulation sensitivity was assessed behaviourally using modulation detection thresholds (MDTs) for a 20 Hz rate. On the same stimulation sites, EASSRS were measured using sinusoidally amplitude modulated pulse trains at 4 and 40 Hz. Measurements were taken using a bipolar configuration on 12 electrode pairs over 5 participants. Results showed that EASSR amplitudes and signal-to-noise ratios (SNRs) were significantly related to the MDTs. Larger EASSRs corresponded with sites of improved modulation sensitivity. This relation was driven by across-subject variation. This result indicates that EASSRs may be used as an objective measure of site-specific temporal sensitivity for CI users.

1. Introduction

Cochlear implant (CI) recipients often understand speech well in quiet conditions but in difficult listening environments their performance worsens and becomes variable. Pre-, per- and post-operative factors account for 22% of this variance (Lazard et al., 2012). A proposed cause for some of the remaining variability in performance is perceptual variance along the tonotopic axis caused by the quality of each electrode neuron interface (ENI) (Pfingst et al., 2008; Bierer and Faulkner, 2010). Reducing these perceptual variations, by adjusting the stimulation parameters of individual sites, has been suggested as a means for improving speech performance (Zwolan et al., 1997; Pfingst et al., 2008).

The ENI affects the ability of an implanted electrode to transmit information to the auditory nerve. Ideally the electrode lies close to the modiolus, which should contain a full compliment of spiral ganglion cells (SGCs) (Long et al., 2014). Variations in electrode placement, tissue growth and local degeneration of SGCs, will cause variations in the ENI and differences in the perception of both spectral and temporal cues.

To account for individual variation along the implanted array, every device is fitted by an audiologist. The fitted parameters for each electrode include the threshold level (T) and comfort level (C). The parameters are stored in the device, and referred to as the MAP.

Commercial CIs transmit both spectral and temporal cues (Xu et al., 2005). Spectral information is predominantly transmitted through the location of stimulated electrodes, and is distorted by current spread and loss of SGCs. Using a focused tripolar mode, stimulation sites with high T levels have been related to broad psychophysical tuning curves which may indicate dead regions in electrical hearing (Bierer and Faulkner, 2010). High variability in T levels across electrodes negatively affects speech performance (Pfingst et al., 2004; Bierer, 2007; Long et al., 2014), possibly due to distortion of the internal representation of the spectrum of the signal.

Compared to normal hearing listeners, CI recipients have reduced access to spectral cues (Friesen et al., 2001). This places increased importance on temporal sensitivity, which is commonly

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assessed using modulation detection thresholds (MDTs). MDTs of CI users have been related to consonant and vowel recognition (Fu, 2002) and to word recognition and speech reception thresholds (SRTs) (Won et al., 2011).

The quality of the ENI varies uniquely along each implanted array. Altering the MAP based on the performance of each ENI has resulted in improved speech performance. Site specific adjustments have been made using a variety of selection criteria and adjustment methods. Zwolan et al. (1997) used 200 ms pulse trains to determine which channels along the electrode array could be discriminated from each other. Channels that were indiscriminable from each other were deactivated. With this altered MAP, seven of nine subjects improved in at least one speech recognition measure. Garadat et al. (2012) used masked MDT performance to create two 10 channel MAPs, one with good across-site mean MDT performance and one with poor performance. The MDTs were determined in the presence of an interleaved masker on the adjacent apical site. The array was divided into five sections of four electrodes. In each MAP two electrodes were retained from each section. One MAP retained two electrodes per section that exhibited the best masked MDTs and the second MAP retained the other two electrodes per section. MAPs with better across-site mean MDTs resulted in better speech recognition. Garadat et al. (2013) extended the previous study by creating a MAP for each participant that improved the mean modulation sensitivity while only removing five electrodes. They endeavoured to remove sites in a distributed fashion across the array, but did not always remove electrodes from all regions of the array. The frequency allocation was redistributed across the remaining electrodes. The modified MAP resulted in a mean SRT improvement of 2 dB over the clinical map and led to better performance than the clinical map for consonant recognition but not for vowel recognition. Zhou and Pfingst (2014) increased the T level of the five electrodes with the poorest MDTs. The T level was increased to artificially increase the loudness of the channel, which improves modulation sensitivity. This adjustment resulted in a mean SRT improvement of 2.4 dB.

Psychophysical evaluation of stimulation sites has illustrated the potential benefit of site-specific adjustments, but these behavioural measures are not always clinically feasible due to their extensive testing time and need for a cooperative participant. Objective measures based on evoked potentials offer the possibility of fast automated evaluation of stimulation sites. Electrically evoked auditory brain stem responses (EABRs) have been used to predict high thresholds and thus sites with poor spectral sensitivity (Bierer et al., 2011; Brown et al., 1990). But neither EABRs nor electrically evoked compound action potentials have shown clinically useful correlations with speech perception tasks or temporal sensitivity (Miller et al., 2008). Here we propose electrically evoked auditory steady state responses (EASSRs) as a measure of site specific temporal sensitivity.

Auditory steady state responses (ASSRs) are neural responses to periodic auditory stimuli (Galambos et al., 1981; Picton et al., 2003) that can be used to predict frequency specific behavioural hearing thresholds (Rance et al., 1995). ASSRs have been related to phoneme recognition, word recognition, word discrimination and speech in noise perception (Dimitrijevic et al., 2001; Picton et al., 2001; Dimitrijevic et al., 2004; Alaerts et al., 2009; Poelmans et al., 2012).

EASSRs can be measured for CI recipients. These recordings are distorted by artifacts from radio frequency transmission and electrical stimulation. Removal of these artifacts (Hofmann and Wouters, 2010) has allowed prediction of behavioural thresholds at clinically relevant pulse rates (Hofmann and Wouters, 2012). We hypothesise that stimulation sites with increased neural responses to modulated auditory input will correspond to sites with improved modulation sensitivity. Thus EASSRs will provide an objective method for assessing the temporal sensitivity of cochlear implant stimulation sites.

2. Materials and methods

2.1. Participants

Five native Flemish-speaking participants volunteered for this experiment. All participants were CI patients of the ENT Department at the UZ Leuven University Hospitals. The details of each participant are included in Table 1, including their word recognition in sentences as evaluated using the LIST sentences (Van Wieringen and Wouters, 2008). Testing was approved by the Medical Ethics Committee of the UZ Leuven (approval number B32220072126) and informed consent was obtained.

2.2. Experiment

Each participant took part in four sessions, each lasting between two and four hours. The measures in successive sessions were: (1) T and C level measurements and loudness balancing, (2) EASSR measurements, (3) loudness balancing for the modulation detection task and (4) modulation detection task. T and C levels were checked again in sessions 2–4.

All stimuli consisted of symmetric biphasic pulse trains with 60 μs phase width and 8 μs inter phase gap, presented at a rate of 900 pulses per second in bipolar (BP) mode (for further information on the choice of stimulation parameters, see Section 4). All stimuli were delivered using the Cochlear Nucleus Implant Communicator (NIC). Bipolar stimulation was used as it may stimulate a more localised region of the cochlea than for monopolar stimulation (Snyder et al., 2008; Kwon & van den Honert, 2006). Pulse polarity is described relative to the more apical electrode. Cathodic first stimulation is defined as the biphasic negative phase first. All psychophysical modulation detection tasks were conducted using cathodic first stimulation. EASSR recordings were obtained using both polarity configurations. This was done so that a comparison could be made to previously published EASSR results (Hofmann and Wouters, 2012). All stimulus magnitudes are reported in Cochlear clinical current units (cu), which is a logarithmic conversion from amperes. For the CIC3 implant, the conversion from cu to current is $i = 10 \times 10^{-6} \times 175^{cu/255}$ μA, and for the CIC4 implant $i = 17.5 \times 10^{-6} \times 100^{cu/255}$ μA.

Stimuli were presented on three electrode pairs for each participant. These electrode pairs were spaced along the array to excite basal, middle and apical regions along the cochlea. All participants used BP+2 mode except E9, who was unable to perceive any stimulus in this mode (Table 1). This participant had the mode changed to BP+5, for which T and C levels were reached on the basal and middle electrode pairs. On the apical electrode, participant E9 did not reach a comfortable percept and this site was excluded. The dynamic range (DR) is defined as the difference between C and T levels. Two electrode pairs were excluded (participants E1 and E2) because the local variation in T and C levels of the clinical monopolar MAP was more than half of the mean DR of these electrodes. The T levels of all included sites varied by <40% of mean DR. Both excluded sites were basal pairs and the T level varied by >69% of the mean DR. Greater differences were assumed to be a sign of highly varying ENI conditions, which cannot be unambiguously assessed with the currently available spatially wide stimulation patterns of bipolar stimuli.