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Research paper

Cortical auditory evoked potentials as an objective measure of behavioral thresholds in cochlear implant users

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A R T I C L E I N F O

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A B S T R A C T

The aim of this study was to assess the suitability of using cortical auditory evoked potentials (CAEPs) as an objective tool for predicting behavioral hearing thresholds in cochlear implant (CI) users. Nine experienced adult CI users of Cochlear™ devices participated. Behavioral thresholds were measured in CI users across apical, mid and basal electrodes. CAEPs were measured for the same stimuli (50 ms pulse trains of 900-pps rate) at a range of input levels across the individual's psychophysical dynamic range (DR). Amplitude growth functions using global field power (GFP) were plotted, and from this the CAEP thresholds were extrapolated and compared to the behavioral thresholds. Increased amplitude and decreased latency of the N1–P2 response was seen with increasing input level. A strong correlation was found between CAEP and behavioral thresholds ($r = 0.93$), implying that the cortical response may be more useful as an objective programming tool for cochlear implants than the auditory nerve response.

1. Introduction

When programming a CI for a particular patient it is necessary to establish the range of electrical currents needed across different electrodes to elicit sounds within the patient's individual perceptual dynamic range (DR). For adults and older children this is done by adjusting current levels on individual electrodes to find the electrical threshold (T-level) and loudest comfortable level (C-level), as reported by the patient. However, CIs are also routinely fitted to babies and young children, for whom giving a verbal response is not possible. For such patients behavioral testing can be highly subjective and time-consuming, so it would be useful to have a reliable objective method for finding the electrical DR. One objective method that has been tried for this purpose is the electrically-evoked compound action potential (ECAP). This is an early latency response, equivalent to wave I of the auditory brainstem response. It has the advantage of being recordable via the intracochlear CI electrodes and therefore providing robust responses, and not requiring the use of scalp electrodes, or for patients to sit still or be in a specific sleep-state. However, ECAP thresholds have been shown to only weakly correlate with behavioral T- and C-levels (e.g. Brown et al., 2000; Hughes et al., 2000) when the behavioral levels are measured using clinically-relevant rates. One reason for the poor correlation is likely to be the low rate at which ECAPs are generally measured, which is far slower than the rates in most clinical CI fittings (McKay et al., 2005). Furthermore, McKay et al. (2013) have shown that incorporating additional ECAP measures such as the effect of rate on ECAP amplitude and the ECAP amplitude response growth slope does not improve the predictability of ECAP measurements for behavioral measurements. ECAPs are therefore not reliable as the sole method of programming CIs for infants, but are often used as a guideline in conjunction with other methods such as electrical stapedius reflex threshold (eSRT) and observed behavioral responses.

Longer-latency cortical auditory evoked potentials (CAEPs) may be a more reliable measure for fitting CIs objectively. Given that the response is from the cortex rather than the auditory nerve, it is

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List of abbreviations: CAEP, Cortical auditory evoked potential; CI, Cochlear implant; CL, Current level; DR, Dynamic range; ECAP, Electrically-evoked compound action potential; eSRT, Electrically-evoked stapedius reflex threshold; NIC, Nucleus Implant Communicator; pps, Pulses per second

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more likely that this response corresponds with perception of the stimulus. CAEP stimuli can include pulse trains similar to those used in clinical fittings. Acoustic CAEP thresholds determined using amplitude growth functions of the N1–P2 complex, have been shown to have good correlation with acoustic hearing thresholds (Lightfoot and Kennedy, 2006). CAEPs can be difficult to record clinically, due to the need for placement of scalp electrodes, a relatively long recording time due to the number of repetitions needed and duration of the response, and due to the large effect of attention/sleep state, which is particularly important when testing children. Recent advances may make clinical recordings of CAEPs for CI users far simpler due to the possibility of recording from extracochlear electrodes (McLaughlin et al., 2013) and improved signal processing techniques such as dynamical embedding that may allow responses to be extracted from noise and artefacts using a small number of trials and channels (Fisher et al., 2007).

CAEPs have been recorded in CI users as a measure of cortical maturation (Sharma et al., 2002, 2005, 2007) and as on objective measure of auditory function (Beynon and Snik, 2004; Beynon et al., 2005, 2002; Kelly et al., 2005). Researchers have shown increasing CAEP amplitude and decreasing latency with increasing stimulus level (Firszt et al., 2002). However, no published study to-date has investigated whether CAEP thresholds evoked by pulse train bursts at clinically-relevant rates are predictive of behavioral thresholds measured at the same rate.

CAEPs do not fully mature until adolescence (Pasman et al., 1999) and so are rarely clinically indicated for finding thresholds in the pediatric population. However, several authors have successfully recorded CAEPs in infants, albeit with significant differences in waveform morphology to those seen in adults (e.g. Pasman et al., 1999; Sharma et al., 2014). The potential clinical use of the technique within a pediatric population should therefore not be discounted. CAEPs have also been recorded consistently in infant CI users at or close to the time of initial activation of the device (Alvarenga et al., 2013; Silva et al., 2014). CAEP morphology (specifically the P1 latency) in infants implanted before the age of 3.5 years has been shown to normalize to that seen in normally-hearing listeners within around 6 months of CI use (Sharma et al., 2002).

This study investigated whether CAEPs evoked by high-rate pulse train bursts of 50-ms duration can be used to estimate behavioral thresholds of the same stimuli in adult CI users. CAEP responses were recorded in a group of CI users, using a range of stimulus levels across the dynamic range from below threshold to comfortably-loud level, and a range of stimulus electrodes (apical, mid, basal). CAEP thresholds were extrapolated from the amplitude growth functions of the global field power (GFP – a measure of the variance of the EEG signal across scalp electrode positions). It was hypothesized that CAEP thresholds would show better correlation with behavioral thresholds than those reported in the literature for ECAPs, and hence would be better suited for objective programming of CIs.

2. Methods

2.1. Subjects

Nine experienced adult cochlear implant users from the Manchester Auditory Implant Programme took part. All used Cochlear™ devices. Participant details can be found in Table 1. The study was approved by the NHS research ethics service.

2.2. Behavioral data

Approximate behavioral thresholds were initially found using a clinical method, whereby stimuli were adjusted in steps of 2 current levels (CL) until the patient consistently reported hearing the sound. Stimuli were 900-pps pulse trains, of 50-ms and 500-ms duration in monopolar (MP1 + 2) mode, delivered on electrodes 3, 11, and 20 (basal, mid and apical respectively). Each biphasic pulse had a phase duration of 25 μs and interphase gap of 8 μs (as was standard in all participants' clinical maps). Stimuli were delivered using the ImpResS CI research interface. Each current level (CL) is a logarithmic step of 0.16 dB.

More-precise behavioral thresholds were then measured for the same stimuli using an adaptive three-interval three-alternative forced choice (3IFC) procedure. The starting level was the approximate threshold plus 20 CL. One interval contained the stimulus and the other two contained silence. The subject was asked to nominate which interval contained the stimulus. The stimulus level was increased after an incorrect response and decreased after two consecutive correct responses. The initial step size was 4 CL for two turning points, then 2 CL for eight turning points. The threshold current level was taken as the average of the last six turning points. Each of the six stimuli was tested in a random order, then, after a short break, the participant completed a repeat run for each stimulus in the reverse order. Threshold was defined as the average of these two runs. These behavioral thresholds were used in the later correlational analysis.

A loudness category scale was then used to find comfortably loud levels for each stimulus (categories included: no sound, barely audible, very soft, soft, medium soft, medium, most comfortable, loud but comfortable, maximal comfort, uncomfortably loud). Stimuli were initially increased in steps of 5 or 10 CL until a level of ‘most comfortable’ was reached. Stimuli were then increased in steps of 2 CL until the level ‘loud but comfortable’ was reached, and further increased in steps of 2 CL until the level ‘maximal comfort’ was reached. The comfortably loud level was taken as the middle value of the range of levels judged to be ‘loud but comfortable’. Each of the six stimuli (3 electrodes, 2 durations) was then played to the participant consecutively at comfortably loud level to check for equal loudness. If necessary, adjustments were made by repeating the described procedure for any stimuli that were not balanced. All presentations were made within the compliance limits of the device. In some cases this meant that a level of ‘maximal comfort’ was not achieved, but a level of ‘loud but comfortable’ was always achieved. The psychophysical dynamic range (DR) was defined as the difference in CL between comfortably loud level and threshold.

2.3. EEG data

EEG data were recorded over two sessions using the Biosemi ActiveTwo™ system with 64 electrodes mounted in a headcap in the international 10–20 configuration. Two additional electrodes recorded horizontal eye movements, located near the outer canthi of each eye, and two further electrodes were used to record vertical eye movements, placed above and below the eye contralateral to the CI. The electrode or electrode(s) directly over the coil site were not used in the recording. The sound processor hung down beneath the headcap, and all electrode wires were directed away from the coil and processor as far as possible to minimise radio frequency (RF) artefact. A recording sampling rate of 2048 Hz was used, and all offsets of recording electrodes (related to impedance) were below 20 μV.

Stimuli were the same as the short duration (50 ms) stimuli used in behavioural testing and were delivered by direct stimulation using the NIC (Nucleus Implant Communicator) interface, and a Freedom sound processor. Each run consisted of 60 stimuli, on a single electrode (3, 11 or 20), with ten presentations at each of six levels (100%, 70%, 50%, 30%, 15% and −20% of the DR) in a random order. The interstimulus interval was randomly roved at