Cortical Auditory Evoked Potentials (CAEPs) and hearing aid amplification in adult patients

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Abstract
Cortical auditory evoked potentials used to study the effect of amplification on the brain in hearing aid users (ACAEPs) were studied for the first time decades ago, along with cortical plasticity induced by auditory rehabilitation. The application of ACAEPs to guide hearing aid fitting and verification and to assist the clinician in the fitting process in hard-to-test populations remains of valuable interest.
Recording ACAEPs can be divided into three approaches: the first, aimed at determining the physiological response detection; the second addressed the question of whether ACAEPs recorded from two audible stimuli at suprathreshold levels were associated with differences between the waveforms; the third, which focused on monitoring them over time.
Several recording factors such as signal level, signal-to-noise ratio (SNR), onset characteristics of the stimulus, frequency response as well as the compression filter were studied but to what extent they can influence ACAEP is still a matter of debate.
The differences that emerge between CAEPs in unaided and aided conditions mean that the principles underlying electrophysiological recording cannot be directly applied when the testing stimulus is processed by a hearing aid device; the latency and amplitude of ACAEP waves are the product of a complex interaction between hearing aid-related parameters and factors that are not yet known.
The interpretation of ACAEP tracks, particularly when comparing aided conditions with different gains or in different points of a time interval, cannot be definitely related to behavioural thresholds until each of the factors involved in hearing aid electrophysiology have been discovered.

Keywords: *Aided cortical auditory evoked potentials; Hearing aid; Sensorineural hearing loss.*

Introduction

Cortical auditory evoked potentials used to study the effect of amplification on the brain in hearing aid users (ACAEPs) were studied for the first time decades ago, along with cortical plasticity induced by auditory rehabilitation. The application of ACAEPs to guide hearing aid fitting and verification and to assist the clinician in the fitting process in hard-to-test populations remains of valuable interest. CAEPs are routinely recorded to estimate behavioural thresholds (approximately within 10 dB of behavioural thresholds) of both normal-hearing and hearing-impaired populations; however, CAEP thresholds may sometimes exceed behavioural thresholds by more than 20 dB (e.g., Ikeda et al., 2010; Glista et al., 2012; Van Maanen et al., 2005), making the hearing aid fitting more challenging. Since the first ACAEP data was published by Rapin and Graziani, different controversies have emerged regarding the recording of electrophysiology under aided conditions. In particular, the data provided by these authors concerned 8 children of whom only five exhibited improved ACAEPs, while the remaining three did not.

The main body of literature concerning ACAEPs can be divided into three approaches to recording electrophysiology with hearing aids: the first is aimed at determining the physiological response detection, comparing the cortical response recorded in unaided conditions with that in aided conditions; the second addressed the question of whether ACAEPs recorded from two audible stimuli at suprathreshold levels were associated with differences between the waveforms; the third application of ACAEPs focused on monitoring them over time to understand how the continuous use of hearing aids may influence them. It is noteworthy that, even though waveforms were absent or weak in hearing impaired patients under unaided conditions, compared to robust waveforms in aided conditions, no conclusive data were reported in the case of comparison between ACAEPs recorded at suprathreshold levels (Billings et al., 2007; Billings et al., 2011). In other words, the amplification effect (i.e., differences between unaided and aided conditions) is more likely to occur near threshold than at suprathreshold levels. For this reason, the effect of amplification by comparing barely audible or inaudible CAEPs with suprathreshold ACAEPs often resulted in significant changes to waveform morphology.

Recording ACAEPs: characteristics, methods, variables

The first factor that was examined was signal level: when recording CAEPs in quiet conditions, it would be expected that, as the intensity of the stimulus increases there would be a shorter latency and a greater amplitude of the waves. Recording CAEPs with a hearing aid means introducing a noise source (through the amplification of background noise or because of circuit noise) into the recording system (Billings et al., 2013); even in quiet conditions, noise is sometimes present in the hearing aid output and can interfere with CAEP intensity/latency patterns (Billings et al., 2007). For this reason, the signal-to-noise ratio (SNR) may need to be taken into consideration when examining the immediate effect of amplification on P1-N1-P2 morphology. Because central auditory system neurons are sensitive to SNR as well as to absolute intensity, the gain provided by a hearing aid might not determine the expected changes in neural processing.

Some investigations have reported CAEP differences in unaided and aided conditions, but without equalising SNRs (Korczak et al., 2005; Miller & Zhang, 2014). For example, Korczak et al. (2005) used ACAEPs to test amplification effects in 14 subjects with either moderate or severe-to-profound sensorineural hearing loss (SNHL) who listened to speech syllables (/ba/ and /da/) that were presented in an oddball paradigm. Hearing aid use resulted in the decreased latency and increased amplitude of the ACAEPs. The change in the waveform was greater at the lower speech level than the higher one (either because of a lack of audibility at the lower intensity when unaided or because of output limitations in the hearing aid with higher intensity sound). Even with hearing aids, SNHL patients had greater latencies than subjects with normal hearing. In addition, the authors found that amplification with hearing aids substantially improved the detectability of all the cortical waves; the amplification of the incoming stimulus may result in better neural encoding of the signal because of the improved audibility that is available immediately after amplification. In contrast, other studies performed in normal-hearing young adults (e.g., Billings et al., 2007; Billings et al., 2011) did not find any changes in ACAEP morphology. Therefore, reported amplification effects might have been influenced by changes in SNRs as well as input modifications from the hearing aid. The interaction between the incoming signal and amplification effect was furtherly studied by Easwar et al. (2012) who did not find evidence of any amplification effect when SNRs were equated at one signal level/noise level combination; Chun et al. (2016) confirmed the findings of Easwar et al. (2012), but, differently from them, they found an amplification effect only for N1 and P2 latencies with a 10 dB SNR condition. They concluded that the effects of amplification may exist only at relatively poor SNRs. Higher absolute signal level was associated with larger amplitudes only when presented in quiet conditions or when background noise was inaudible (Billings et al., 2012), and ACAEPs are mostly influenced by SNR rather than absolute signal level. Specifically, they found that when the amplification effect was absent, the SNR ratios between the unaided and aided conditions were very similar.

To explain the effect of SNR on ACAEPs, Billings et al. (2011) compared CAEP morphology with and without hearing aids, while keeping the incoming signal in the ear canal at the same intensity level. The results showed that ACAEPs tended to present smaller amplitudes and longer latencies when measuring them with hearing aids; SNR decreased as hearing aid gain increased because of the amplification of the background noise, but it may vary depending on the gain setting and the examined frequency. A greater effect of amplification was found for P2 with respect to N1, even though they represent acoustic feature processed in different cortical areas.

Onset characteristics of the stimulus are also a contributing factor in ACAEP morphology, and digital hearings aids can dramatically and differently modify the signal onset and thus ACAEPs in an unpredictable way (Jenstad et al., 2012).

The frequency response as well as the compression filter of the hearing aid may lead to audible background noise in certain spectral ranges but not in others as a result of the programmed fitting, further determining the SNR. In particular, compression modifying the first 30–50 ms of the incoming stimulus (rise slope, rise time, overshoot of the onset) may contribute to determining the morphology of ACAEPs (Onishi & Davis, 1968). Easwar et al. (2012) observed shortened rise times and overshoots at the onset of the stimulus (tone burst) in hearing-aid-processed stimuli with fast compression (attack/release time: 10/60 ms). Because N1-P2 CAEP is an "onset response" generated when many cortical pyramidal cells fire synchronously at the onset of a stimulus, these changes in amplitude or frequency made by hearing aid processing may influence neuronal activity (Onishi & Davis, 1968; Marynewich et al., 2012). Other factors may include channel-specific compression time constants, noise reduction algorithms and adaptive directionality.

Previous studies have explored the effects of digital versus analogue technology on ACAEPs. Marynewich et al. (2012) reported smaller ACAEP amplitudes when recording with digital hearing aids compared to analogue hearing aids, and none of the hearing aids resulted in a reliable increase in response amplitude when compared to unaided across the conditions; digital hearing aids showed significantly delayed ACAEP latencies. Jenstad et al. (2012), studying digital hearing aids with linear amplification, demonstrated that they may alter the rise time of the stimuli so that maximum gain was reached well past 30 ms after stimulus onset, resulting in altered ACAEPs.

ACAEPs are usually elicited by tone-burst stimuli; in contrast, brief and transient stimuli such as clicks and tone pips are not ideal for measuring hearing aid function because they do not effectively and consistently activate hearing aid circuitry.

The use of speech sounds such as vowels and consonants was also tested to record ACAEPs. The acoustic characteristics of complex sounds can be reflected in the form and latency of these potentials; the duration of the spectrum of speech sounds enables the amplified stimulus to have similar performance in relation to its functioning in everyday situations. Depending on the spectral components of the speech sound and on the prescribed fitting algorithm, the effect of amplification on ACAEPs may vary. For example, Durante et al. reported responses that were significantly more present in ACAEPs for the sounds /g/ and /t/ than for the sound /m/; they explained this difference on the basis of the lower amplification prescribed for low frequencies, which are the main spectral components of the phoneme /m/. ACAEPs with speech tokens were also recorded by Vanaja et al. who observed an improvement in the aided conditions in 8 out of 9 SNHL patients for the /ma/ sound, in 6 for /ga/ and in 4 for /ta/; ACAEP latencies were longer than those obtained for persons with normal hearing. Sensitivity to different speech tokens may vary: aided CAEPs showed reliable differences between the syllables 'see' and 'shee' (Tremblay et al., 2006), but did not distinguish between the syllables /ma/, /ga/ and /ta/ (Munro et al., 2011).

Different methods have been proposed for recording ACAEPs. The simplest is recording in the free-field while the patient wears his/her hearing aids; obviously monoaural testing needs to reduce the contribution of the non-test ear with an earplug. The second method involves recording the hearing aid output offline, either in a coupler or a mannequin, and then delivering it through insert earphones to the participant. In the third approach, the stimulus is presented using direct audio input through the hearing aid worn by the patient (Glista et al., 2012; Easwar et al., 2012; Billings et al., 2013).

Monitoring CAEPs in adult-onset hearing loss

Differently from deaf children who are at risk of abnormal development of the auditory cortex and, consequently, delayed or absent language, adults who experience hearing impairment present structured central auditory pathways. For this reason, monitoring CAEPs in adults who wear hearing aids or use cochlear implants has a different meaning and aims to identify an acclimatization effect through changes in wave morphology, latency and/or amplitude that can be correlated to speech perception improvement.

Few studies have identified asymmetrical CAEPs in experienced unilateral hearing aid users, and the methodologies and designs did not allow for definitive conclusions to be made about an acclimatization effect. Gatehouse and Robinson (1996) studied CAEP recordings in response to 500 and 2000 Hz tones at 65, 80, and 95 dB sound pressure level (SPL) in a 69-year-old long-term unilateral hearing aid user; the patient had been aided in the right ear for 4 years with an average daily use of 8 h. For the 500 Hz frequency there was no difference in N1 and P2 amplitude between the ears at all levels, but for the 2000-Hz stimulus, the aided ear had a larger amplitude for the 95 dB SPL presentation level. The authors concluded that these results supported a potential acclimatization effect and were the first to suggest a possible use of CAEPs to investigate auditory electrophysiological changes after rehabilitation.

Munro et al. (2007) studied ear asymmetry in the auditory brainstem response (ABR) of a group of hearing aid users with a minimum experience of 2 years and a self-reported daily use >5 h, which was compared with a group of patents with symmetric high-frequency SNHL prior to hearing aid fitting. Clicks were presented unilaterally at 70, 80 and 90 dB HL. The analysis of wave V morphology revealed a higher amplitude at 70 and 80 dB HL levels in the aided ear compared to the unaided ear, which was interpreted as an acclimatization effect at the level of the brainstem.

Bertoli et al. (2011) investigated CAEPs in 30 patients, ten experienced unilateral hearing aid users, ten experienced bilateral hearing aid users and ten normal-hearing subjects. The hypothesis tested was that fitted ears may show higher CAEP amplitudes and shorter latency compared to non-fitted ears. Stimuli of 500, 1000, and 2000 Hz at 55, 70, and 85 dB SPL were presented monaurally to both ears. Data analysis did not reveal any interaction between ear, frequency, and level observed for either latency or amplitude, with the exception of the unilateral group; specifically, an increased P2 amplitude for the 2000 Hz stimulus in the fitted ear of unilateral users was found. The authors hypothesised that larger P2 amplitude in the fitted ear of the unilateral group may reflect a more strenuous auditory processing, perhaps as a result of asymmetric amplification. Speech recognition testing did not show any significant difference between the unilateral and bilateral hearing aid user groups, although the recognition threshold was significantly better in the aided ear compared to the non-aided ear of unilateral users.

Dawes et al. (2014) investigated the relationship between CAEPs and speech recognition in noise following for 12 weeks a group of patients with a mild-to-moderate sloping high frequency SNHL who were unilaterally and bilaterally fitted. The N1 and P2 were recorded at 500 and 3000 Hz tones presented at 65, 75, and 85 dB SPL to both ears. They did not report any changes in CAEPs with a statistically significant 2% improvement in aided speech recognition over time, which was consistent with a general test–retest effect. They concluded that an acclimatization effect was not demonstrated after 12 weeks of hearing aid use.

A study conducted by Rao et al. (2017) among 22 patients with mild-to-moderate SNHL who were first-time hearing aid users tried to find a relationship between the P300 wave and speech perception through a Hearing in Noise Test (HINT) after 4 weeks of an auditory training programme. Physiological changes, such as significant P3a amplitude reduction, were observed, while perceptual benefits assessed by HINT were not found.

Finally, Giroud et al. (2017) monitored behavioural and electrophysiological auditory and cognitive-related plasticity in older adults aged between 60 and 77 years who were moderately hearing-impaired and who were hearing aids users fitted with different protocols. All patients were tested 5 times across three months, and EEG measurements were recorded after stimulation with naturally high-pitched fricative (/sh/, /s/, and /f/) syllables. The authors observed longer latencies in the P1 and N1 peak in hearing aid users and, as expected, higher processing effort with respect to the normal-hearing control group. Using global field power (GFP) as a measure of processing effort, a decrease of the GFP of cognitive-related CAEPs was demonstrated among hearing-impaired patients after three months, suggesting that a minimum of twelve weeks is required to observe an acclimatization effect. Furthermore, a significant lowering of GFP in the P3b of the group who was fitted with nonlinear frequency compression (NLFC) was found compared to the group with NLFC off.

Conclusion

From the first ACAEP reports by Rapin and Graziani to the more recent revisions of ACAEP investigations, various concerns still need to be addressed before their findings can be put into routine clinical practice. The major question remains: "what are the main variables that could affect CAEPs when a hearing aid is worn?" It is evident that hearing aid signal processing causes many acoustic modifications to a stimulus (e.g., rise-fall time, signal level, etc.), but to what extent it can influence ACAEP recording is still a matter of debate.

To sum up, the differences that emerge between CAEPs in unaided and aided conditions mean that the principles underlying electrophysiological recording cannot be directly applied when the testing stimulus is processed by a hearing aid device; the latency and amplitude of ACAEP waves are the product of a complex interaction between the aforementioned hearing aid-related parameters and factors that are not yet known. The interpretation of ACAEP tracks, particularly when comparing aided conditions with different gains, cannot be definitely related to behavioural thresholds until each of the factors involved in hearing aid electrophysiology have been discovered.

Of course, the presence of ACAEP waves in aided versus unaided conditions may suggest to the clinician the detectability of the incoming signal by the patient, but an adequate fitting needs to relate the gain to aided thresholds, which means understanding how much of the sound is effectively amplified and listened to by the patient, and whether this information can be inferred from ACAEP morphology.

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