Recommended Procedure

Cortical Auditory Evoked Potential (CAEP) Testing

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General foreword

This document presents Practice Guidance by the British Society of Audiology (BSA). This Practice Guidance represents, to the best knowledge of the BSA, the evidence-base and consensus on good practice, given the stated methodology and scope of the document and at the time of publication.

Although care has been taken in preparing this information, with reviews by national and international experts, the BSA does not and cannot guarantee the interpretation and application of it. The BSA cannot be held responsible for any errors or omissions, and the BSA accepts no liability whatsoever for any loss or damage howsoever arising. This document supersedes any previous statement on cortical auditory evoked potential assessment by the BSA and stands until superseded or withdrawn by the BSA.

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1. **Introduction**

This document is not intended to provide guidance on specific circumstances or on interpretation of results. It is important that the competent person carrying out, or responsible for, the test (the ‘tester’) uses professional judgement when deciding on the particular approach to be used with each person being tested (the ‘subject’), given the specific circumstances and the purposes of the test, and the tester’s level of competency.

The term ‘shall’ is used in this document to refer to essential practice, and ‘should’ to refer to desirable practice. Unless stated otherwise, this document represents the consensus of expert opinion and evidence as interpreted by the Professional Guidance Group of the BSA in consultation with its stakeholders (Appendix 1). The document was developed in accordance with the BSA Procedures for Processing Documents (BSA).

1.1. **Historical Setting**

Hallowell Davis (Davis, H.; Davis P.A.; Loomis, A.L.; Harvey, E.N.; Hobart 1939) identified the auditory cortical evoked response in 1939. The response is an example of an obligatory exogenous “event-related potential” (ERP) and is most easily identified using an averaging technique, in which a stimulus is presented repeatedly and the post-stimulus EEG is averaged. The computers necessary for averaging were originally analogue but the availability of digital computers facilitated the ease and precision of ERP measurement. The term “Evoked Response Audiometry” (ERA) covers all ERPs to auditory stimuli. Historically many different terms have been used to describe auditory ERPs of cortical origin, such as the slow vertex response (SVR) or the auditory cortical potential (ACP). However current recommended terminology to describe auditory ERPs of cortical origin is cortical auditory evoked potentials (CAEPs). Much of the basic research on CAEPs dates from the mid-1960s to mid-1970s; pioneers from the UK included Harry Beagley and Bill Gibson.

1.2. **Characteristics and uses of the CAEP**

The mature supra-threshold CAEP comprises a series of peaks and troughs usually termed P1 (rarely labelled) at typically 50-70 ms, N1 at typically 100-130 ms and P2 at typically 200-250 ms.
Response morphology is dependent on age, arousal state, attention, stimulus and presentation parameters.


One of the most important and clinically useful aspects of the CAEP is that in adults, the response can be observed close to, and therefore can be used as an objective estimator of the auditory threshold (Hyde et al. 1986; Hyde 1997; Tsui et al. 2002). This has obvious applications in patients that cannot or will not produce reliable responses during pure-tone audiometry (PTA).

The response may also provide an indication of the maturation of the auditory pathway (Sharma et al. 2002). For example, Sharma et al. (2005) used the CAEP to demonstrate that the cortical responses of children who received cochlear implantation before the age of 3.5 years matured more quickly than the responses of children implanted after 7 years, suggesting a sensitive period of neural development.

As with other auditory evoked responses, the size of the response diminishes and its latency increases as the stimulus level is reduced towards the patient’s threshold (Picton et al. 1970). Figure 1 illustrates this for a 4 kHz tone burst stimulus in an adult whose PTA suggested a 4 kHz threshold of 20 dBHL. Responses are observed at stimulus levels of 30 dBHL and above.
Figure 1
An example of CAEPs at a number of stimulus levels in dBHL. The bold lines are the grand averages of the three sub-averages at each level. A 900 ms recording window was used, with 250 ms being pre-stimulus onset. Stimulus onset is at the vertical dotted line. In the table, CC=correlation coefficient, RN=residual noise in µV, S/N is signal (response) to noise ratio, p=p-value.

The CAEP is triggered by the onset or offset of a transient stimulus or by a perceptible change in an ongoing signal such as a gap in a continuous sound, a change in level or a change in frequency of a continuous tone. The largest responses occur for louder stimuli and for stimuli with a short rise time (Onishi & Davis 1968).

Another important aspect of the CAEP is that it may not be reliably present in drowsy or sleeping patients (Ornitz et al. 1967). As a result, CAEP testing is performed in awake and alert patients.

It is generally accepted that the CAEP does not fully mature until the late teens (Sharma et al. 2002; Wunderlich et al. 2006; Sussman et al. 2008) but that the
technique can be attempted in older children, although auditory brainstem response (ABR) or 80 Hz auditory steady-state response (ASSR) methods can be inaccurate because of muscle activity in awake patients. In awake newborns, infants and young children the immature response is usually recordable for stimuli well above threshold and a resurgence of interest in the last decade has revealed that whilst the response is not a reliable predictor of the hearing threshold, it may nevertheless be capable of providing clinically useful information. Appendix 2 provides more information of this application.

2. Scope

This document describes the use of the CAEP in hearing threshold estimation in adults and older children (typically over 8 years). Appendix 2 briefly summarises the use of the response in supra-threshold testing in infants; a technique not yet in common clinical use but attracting considerable research interest. The subject of conducting CAEP tests with the stimulus presented via a hearing aid is beyond the scope of this document; the reader is warned that there is some controversy on this matter, with some experts suggesting that the transient stimulus may be processed by the hearing aid in an unexpected way, with potential to make misleading conclusions. It has been noted that some studies have used CAEPs to assess aided responses in normally hearing subjects and obtained results that may not be applicable to patients with hearing loss. There is evidence that the latency and amplitude of the CAEP is sensitive to the signal to noise ratio of the stimulus rather than to the stimulus level (Billings et al. 2009) so the internal noise of the hearing aid (heard by normally hearing subjects but not by hearing impaired patients) can influence aided CAEP measurements. A further concern in CAEP aided response measurements relates to the transient nature of the stimuli (tone bursts or speech tokens) which, unlike normal speech, may be shorter in duration than the attack time of a hearing aid’s compression circuit thus leading to an unrepresentative assessment of hearing aid performance.

3. Equipment & Test Environment

3.1. Equipment

The CAEP may be recorded on most popular auditory evoked potential systems whose most common clinical application is ABR testing. Table 1 offers suitable basic
stimulus and recording parameters. However, specialist CAEP systems are available that offer greater ease of use, speed of testing, narrow-band masking noise and objective response scoring. Unfortunately such systems do not additionally perform ABR tests and few centres have both types of system (Carter et al. 2010).

All electrophysiological equipment shall satisfy the electrical safety requirements detailed in BS EN 60601-1 for type BF equipment and be tested by a qualified person on an annual basis.

3.2. Test Environment

For hearing threshold estimation, the patient shall be clearly visible to the tester. The patient shall not be able to see or hear the tester adjust the equipment. When the test is controlled from outside the audiometric test room, the patient shall be monitored visually through a window or by a closed-circuit TV-system and acoustically via an intercom to ensure that any movement or patient-generated noise is identified.

Excessive ambient noise will affect the test results, and ambient noise shall not exceed the levels set out in BS EN ISO 8253-1. These are the levels appropriate for routine PTA. The problems caused by ambient noise are greater when testing by bone conduction or loudspeakers as there are no earphones in place to reduce the noise reaching the ears. In general, the ambient noise should not exceed 35 dB(A). A higher level ambient noise may be tolerated if tests down to 0 dBHL are not conducted.

For all evoked measurements the test environment should be electrically quiet, with steps taken to eliminate local sources of electrical interference. These include the use of light dimmers (minimum interference occurs when such lights are switched off or are fully on rather than dimmed), microwave ovens, lift shaft motors, X-ray equipment, mobile phones, staff bleep systems, surgical diathermy and pulse oximeters. The vulnerability of CAEP testing to electrical interference is far less than ABR testing because lower filters are used and the response is larger.

4. Staff Training

Staff undertaking CAEP tests on patients and reporting on their results shall receive specialist training and ensure they practice within the limits of their clinical
competence. Some introductory instruction is a component of some British graduate or post-graduate courses in Audiology but this is unlikely to be sufficient and attendance on a specialist course or a programme of structured private study is advised. Recently trained staff should arrange to receive mentorship and support from an experienced colleague and arrange for their practice to be peer reviewed.

If tests are to be conducted on non-clinical medico-legal patients it is wise to obtain clear understanding with the employing health body that they accept responsibility for this activity. An alternative, for example in private practice, is to arrange appropriate professional indemnity and public liability insurance.

5. Preparation for testing

5.1. Preparation of test patients

The tester should adopt an effective communication strategy with the patient throughout. This shall take account of the patient’s age, hearing, language skills and any other possible communication difficulties, including any suspected non-organic hearing loss (NOHL). Testing shall be preceded by otoscopic examination and tympanometry (see relevant BSA recommended procedures) and the findings recorded, including the presence of any wax. Occluding wax may be removed prior to testing but if wax is removed the procedure shall be documented and undertaken by someone who is qualified and competent to do so.

If there is a likelihood of ear canals collapsing with supra-aural earphones in position this should be recorded as it may lead to measurement of a false air-bone gap. In some cases the use of insert earphones (e.g. Etymotic ER3 and ER5) will avoid this problem.

The appointment letter should include instructions to avoid exposure to loud noise in the 24 hours prior to the test as this can cause a temporary hearing loss. The patient should be asked if they have complied with this instruction. ‘Loud’ can be determined by having to shout or use a raised voice to communicate at a distance of 1 metre or 3 feet. If the results may have been affected by recent noise exposure then it may be necessary to re-test the patient at a time when they have had no recent exposure to noise.

The identity of the patient shall be checked according to local policy. Additionally
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testers should be alert to the possibility of identity fraud. If required by the instructing solicitor or clinician in medico-legal tests, the appointment letter should instruct the patient to provide appropriate documentation confirming their identity (e.g. driving licence or passport).

In the case of a patient with a learning disability and/or autism, the presence of hypertactility may cause considerable anxiety about the possibility of electrodes or transducers on the head. Pre-appointment work can be carried out involving the patient’s care team introducing the individual to electrodes and, for instance, a pair of headphones in a home environment.

If applicable, inform the patient about intercom facilities.

5.2. Patient Instructions

The detail given to the patient (or their carer/parent/guardian) immediately prior to testing will depend on the test, the clinical background and age of the patient. In all cases the patient should be instructed that the test is automatic and that they are required to sit quietly, with the transducers and electrodes (“sensors” may be a less worrying term) in place. If the patient expresses concern, they should be reassured that the electrodes are passive and do not introduce any electricity. The likely duration of the test should be given, together with what the patient should do if they want a break. There are some patient groups for whom the test may require more than one test session to achieve any thresholds. This possibility should be discussed with both the patient and their care team prior to the commencement of the test. Consent for testing shall be obtained from the patient or their advocate. If there is to be no post-test discussion of results (as may be the case for medico-legal tests) then this should be disclosed prior to testing. For cases of suspected NOHL it may be helpful to first outline the tests to be performed (which may include a pre-CAEP PTA), highlighting the objective nature of the cortical test. It is not uncommon for the patient to then provide an accurate PTA or at least a PTA with a smaller non-organic component than previously recorded. After giving the test instructions, remove any hearing aids, headwear or ear-rings that may obstruct the correct placement of the transducers, cause discomfort or affect sound transmission. Wherever possible, hair, scarves etc., should not be allowed to sit between the ear and the transducer. Unlike conventional PTA in which any spectacles should be removed, CAEP testing requires that the patient be alert yet not physically active and in adult testing this is most conveniently achieved by asking the patient to read a magazine or watch a silent video (Lavoie et al. 2008). The patient should wear any
spectacles appropriate for this, taking care they do not compromise correct and comfortable placement of transducers.

5.3. **Electrodes**

The following sterile procedure is recommended for skin preparation. The skin should be gently and carefully abraded using a suitable sterile abrasive electrode paste and a clean gauze or cotton bud. An alternative is the use of a disposable abrasive pad. Disposable electrodes are recommended. Electrodes with integral adhesive of the type often used in ABR testing are usually difficult to attach securely at the Cz site unless the patient is bald. Disposable EEG-type electrodes with electrode paste, secured by tape, are available and may be used with success.

Artefact size from induced electrical interference is proportional to the difference in the electrode impedances. This difference in impedances is most easily minimised by ensuring all electrodes have low impedances. The impedance should be similar across electrodes and no more than 5 kΩ. However in good recording conditions and in an electrically quiet room higher electrode impedances can be tolerated.

A single channel recording is recommended, with electrodes located as follows:

- **Positive electrode:** vertex (Cz). A high forehead position may reduce the response amplitude and can be tolerated but a mid-forehead position is not appropriate.
- **Negative electrode:** low mastoid (on either side: the response may be recorded from either mastoid). Sufficient space should be allowed for a bone vibrator to be placed on the mastoid above the electrode without interfering with the electrode.
- **Common electrode:** other mastoid or mid-forehead.

This configuration should result in N1 being plotted downwards on the display. If this is not the case then the positive and negative electrode connections should be reversed.

An alternative to the 3-electrode montage described above is to adopt a 4-electrode arrangement in which the positive is at the vertex (Cz), the negative is a linked pair of electrodes (using “jump leads”) on the mastoids and the common is placed mid-forehead (Lightfoot & Kennedy 2006). This is believed by Lightfoot & Kennedy (but not verified) to be associated with a reduction in patient-generated myogenic noise and a corresponding slight improvement in signal to noise ratio.
6. Stimuli

6.1. Calibration

Auditory tonal stimuli shall be calibrated to the relevant part or parts of BS EN ISO 389 relating to pure tones, depending on the transducers used. BS EN ISO 389-6 which relates to the very brief stimuli used in ABR testing should not be used for the calibration of tonal stimuli used in CAEP testing. The calibration should be checked annually by a qualified person. For the purpose of calibration, the tone should be made continuous (or near-continuous for example by selecting a rise/fall time of 1 ms, a plateau time of 997 ms and a repetition rate of 1/s). The system may then be calibrated as a pure-tone audiometer. Additionally, testers should adopt and apply the principles daily subjective “Stage A” checks given in the BSA PTA recommended procedure.

Where non-tonal stimuli such as speech tokens or white noise are used their calibration details shall be provided by the manufacturer or determined by an appropriate panel of normally hearing subjects, tested behaviourally.

6.2. Stimulus type

A linear-ramped tone burst is most commonly used for hearing threshold purposes as this allows an objective estimation of the audiogram. A rise/fall time of 10 ms at frequencies of 1 kHz and above (20 ms at lower frequencies) provides a good compromise between frequency specificity and response size. Some systems specify rise/fall time in time (ms) whilst in others it is specified in cycles. Care is needed to select the appropriate values.

Tone burst plateau time is a parameter over which there is some debate. A longer time (e.g. 200 ms) will minimise the effects of temporal integration but it is likely that it is only the first 30-60 ms of the stimulus that evokes the response (Cody & Klass 1968; Weber 1970; McCandless & Best 1966) and a longer duration is likely to decrease the magnitude of the response to the following stimulus so extending the stimulus beyond this may be pointless. A plateau time of 100 ms carries a theoretical disadvantage: the offset of a tone burst also evokes an offset cortical response and the N1 of this second response will destructively interfere with the P2 of the tone onset response. In practice the offset response is very small, so such
destructive interference is probably negligible.

Any standard audiometric transducer may be used.

7. Masking

For tone burst stimuli, the normal PTA rules apply to the need for masking and when it should be applied. The plateau masking method is too time consuming to be applied. Instead the level of narrow-band masking noise should be calculated for a given stimulus level as follows:

\[ M_{dB} = S_{dB} - T + 10 + A_{nt} \]

where:

- \( M_{dB} \) is the narrow-band masking noise level (calibrated to normal audiometric masking standards, i.e. is calibrated in terms of effective masking);
- \( S_{dB} \) is the stimulus level (calibrated to normal audiometric pure tone standards);
- \( T \) is the minimum transcranial transmission loss (inter-aural attenuation) associated with the transducer (a figure of 40dB is quoted for supra-aural earphones in the BSA PTA recommended procedure but many practitioners consider 45 dB to be a more appropriate figure (Lightfoot et al. 2010));
- \( A_{nt} \) is the air-bone gap in the non-test ear at the test frequency.

In the client groups for whom CAEP testing is most useful, we often do not know \( A_{nt} \) so an educated guess is required, based on available information. A reasonable compromise would be to use a value of 30dB in cases of a non-peaked tympanogram. Even so, there may be a risk that the level of noise used for masking may, in certain cases, lead to overmasking or undermasking; the thresholds given in the CAEP report should be qualified where uncertainty exists.

The formula above relates to narrow-band masking noise. One common problem with the design of most ERA equipment primarily designed for ABR testing is that manufacturers frequently provide only wide band noise for masking purposes, for which there is no international calibration standard. If narrow band noise is available then this should be used. One practical, albeit inelegant, solution is to use
a conventional audiometer and associated earphone to supply the narrow band masking noise.

8. Data Collection

8.1. Stimulus repetition rate

This parameter represents a compromise between response size and speed of testing. The N1-P2 response takes typically 10 s to fully recover and if the objective was to record the largest possible response regardless of test time a repetition rate of one stimulus every 10 s would be appropriate (Appleby 1964; Davis et al. 1966). If stimuli are presented more rapidly than this then a diminished response will be recorded. The majority of this response habituation occurs following the first few stimuli (Walter 1964; Ozesmi et al. 2000). However the purpose of averaging is to improve the response signal to noise ratio (SNR) and the more sweeps are averaged per minute the better. In adults the optimum improvement in SNR corresponds to a repetition rate of one stimulus every 1 to 2 seconds (a rate of 0.5 to 1.0 per second) (Rapin 1964; Davis & Zerlin 1966). The response recovery time is thought to be somewhat longer for the immature response of older children, requiring a slower repetition rate (0.25 to 0.5 per second). Further research is needed in this area.

Using these repetition rates the response to the first stimulus in an averaging sequence will be untypically large as it will have been preceded by a period of silence; the second will be somewhat smaller and so on.

Habituation of the response is thought to be greatest for predictable stimuli, as used in conventional averaging, with somewhat greater response amplitudes recorded in response to stimuli with less predictability. Varying the stimulus repetition rate (or inter-stimulus interval) may reduce habituation (Rapin 1964; Rothman et al. 1970) as might randomising the ear to which the stimuli are presented (Butler 1972). However standard auditory evoked potential systems do not offer this functionality. Lightfoot & Kennedy (2006) used the CED system to investigate whether a variety of stimulus manipulations increased response size but no effect was significant. However their study did not include long exposure to monotonous stimuli as reference. An alternative explanation to their negative findings could be that the novelty value of unpredictable stimuli is a temporary effect that needs to be applied sparingly.
It has been suggested that the CAEP from individuals with some pathologies, such as Down Syndrome, are not affected by habituation (Schafer & Peeke 1982).

8.2. **Number of sweeps**

In research, where the latency or amplitude of a response must be accurately defined, a large number of sweeps (100 or more) are often used to obtain an averaged waveform with a high SNR. In clinical hearing threshold estimation the objective is to decide whether, for a particular stimulus level, a response is present or absent and for reasons of clinical efficiency this is done in the minimum time.

For large responses (presumed to be supra-threshold) only 5 to 30 sweeps may be needed per sub-average to correctly identify a response; the smaller responses close to threshold will require more sweeps in order to achieve the SNR that is needed to identify a response with an acceptable degree of confidence (see section 10.3). Still greater numbers of sweeps are usually required to reduce the residual noise of an average waveform before it can be concluded that no response is present (section 10.4).

The number of sweeps used at a given stimulus level therefore depends on the size of any response seen and the residual noise in the waveform. The issue of large responses being seen at the start of an averaging sequence (see section 9.1) is a potential trap for testers who, on seeing an apparent response after just a few sweeps, terminate the average. To guard against this error it is vital that the number of sweeps per grand average is never less than 10, that responses are always replicated and that the methods for analysis (see section 10) are followed.

8.3. **Replication**

In systems that do not have objective scoring, the subjective visual analysis of waveforms requires that there are at least two sub-averages, to allow the tester to judge whether a potential response is sufficiently repeatable to be accepted as genuine. Sub-averages should be superimposed and optionally displayed with their grand average. In the absence of objective scoring facilities, an unreplicated waveform should never contribute to the definition of threshold but is acceptable in the initial phase of testing (see Section 9.8).
8.4. ** Artefact rejection level**

This is the voltage limits above which an epoch (a single sweep) of data is rejected since it is likely to contain considerable non-response activity, often associated with muscle activity. A value of around ±50 µV is recommended. Few epochs should be rejected; it is particularly advantageous to capture (not reject) the epochs associated with the first few stimuli in an averaging run as their signal to noise ratio will be particularly favourable. In research it is usual to employ electrodes positioned to detect eye blinks for the purpose of artefact rejection since blinks are one common source of muscle interference. This is generally not needed in the clinical setting.

8.5. ** Filters**

The spectrum of the near-threshold CAEP is greatest in the 2-10 Hz range which shifts towards the lower frequencies as threshold is approached and in order to optimise the SNR, the incoming electrical activity is filtered prior to digitisation and averaging. A low (high-pass) filter setting of 1 Hz and, where available, a high (low-pass) filter setting of 15 Hz should be used. In some systems the lowest available low-pass filter setting is 30 Hz.

A narrower bandwidth of 5 Hz to 9 Hz has been suggested (Bacon et al. 1990) which was derived from an analysis of CAEP responses at 40 dB and 60 dB above the subjective threshold but it is the responses close to threshold that are of greatest clinical interest. In research a low-pass setting of 100 Hz is common, which provides more accurate determination of response latency but at the expense of more noisy waveforms.

8.6. ** Timebase/window length**

This is the period over which the incoming electrical activity is recorded and averaged. For the purposes of response detection any genuine response must be clearly distinguishable from ongoing spontaneous noise so it is important for the window to include regions where no response is likely as well as the region where a response is expected. A minimum of 500 ms is needed, which starts at stimulus onset. However the inclusion of an additional 200-300 ms pre-stimulus baseline can be helpful in judging the background activity, thus aiding the process of identifying a response as a feature which is distinct from the noise. A time base of 800 ms
including 250 ms pre-stimulus baseline would be ideal but not all systems allow this.

8.7. Display

The vertical (voltage) display scale shall be fixed (not automatically adjusted by the software as a result of the waveform size) and such that small responses can be seen yet several test levels can be displayed on the same chart, in order of descending stimulus level. A display aspect ratio of typically 100 ms = 5 µV is suitable. An automatic display scale shall not be used.

All sub-averages should be displayed, superimposed, unless there is a good technical reason for not doing so in which case a comment should be made in the clinical notes for the purpose of future reference. Waveforms should not be discarded simply because they do not show good correlation with other sub-averages. If a “response” in one waveform is not repeated in other waveforms and the patient’s state of arousal has not significantly altered it is likely to be noise masquerading as a response.

Grand averages may be displayed superimposed with their constituent sub-averages or displayed slightly above or below their sub-averages.

If the timebase/window includes any pre-stimulus baseline the time of stimulus onset shall be indicated.

8.8. Choice of stimulus levels

The starting level will depend to some degree on what is already reliably known for the patient but this is often very little. A stimulus at a moderate level (e.g. 60 dBHL) is usually chosen. If this initial level reveals an obvious (albeit unreplicated) response reduce the level in 20 dB steps, then use 10 dB steps to define the threshold. If the initial level fails to reveal a likely response (replication at this stage is often not a good use of time) then increase by 20 dB. If no likely response is seen continue to increase in 10 dB steps.

The use of a 5 dB step size when near threshold is at the discretion of the tester and the clinical or medico-legal requirements of the case.

Replication and the formal application of criteria for response presence and response absence (see below) are necessary only for those levels that define the
threshold. However if the status of an unreplicated waveform is difficult to judge, replication is appropriate.

8.9. **Maintaining patient arousal**

Drowsiness and both natural and sedation-induced sleep can make the response unpredictable, so the patient’s state should be monitored by the tester and action taken if appropriate. Patient eye closure should be avoided as this is associated with EEG alpha activity which may be mistaken for a response.

Protracted test sessions should be avoided as poorer responses have been noted when the test session extends beyond 30 minutes (Davis & Zerlin, 1966).

A double blind placebo controlled crossover study (Kennedy et al. submitted 2014) concluded that a moderate amount of caffeine does not enhance the N1-P2 response.

The tester should have a range of options available to them to maintain patient arousal, for example reading or, for patients who cannot read, watching a silent video.

9. **Data Analysis/Interpretation**

9.1. **Who should interpret & report?**

There are many patient and technical issues capable of influencing the quality of recorded CAEPs. Examples include patient drowsiness, eye closure, patient-generated noise or muscle activity, electrical interference and difficulties with electrode security. It is good practice for the tester to document these for future reference and, whilst it is usually possible for someone not present during testing to accurately interpret and report on a case, the tester is undoubtedly best placed to interpret and report the results of a CAEP session. The decisions required for appropriate test strategy include skilled response interpretation during the recording process so anyone sufficiently skilled to perform the test has the skills necessary for interpretation and reporting. It is nevertheless valuable for the tester
to seek a second opinion and peer review, particularly in challenging cases. The report shall not be prepared by a person that does not possess the training, skills and experience needed to perform CAEP testing.

9.2. **Objective measurements**

Some systems specifically designed to conduct CAEP tests offer objective response scoring and estimation of the residual noise in the waveforms. The Frye Electronics HEARLab system, developed at the Australian National Acoustics Laboratories (NAL) uses statistical analysis based on Hotelling’s $T^2$ statistic, resulting in a p-value (VanDun et al. 2012). The Cambridge Electronic Design CERA system, developed in Liverpool UK, uses a combination of SNR and sub-average correlation to give a p-value. Both systems also estimate residual noise.

These objective measurements have an obvious attraction when testing medico-legal patients but in all cases, objective measurements should be used as an adjunct to the tester’s interpretation described below. The tester should override the statistical information if they feel it is likely that it is the result of an artifact.

The primary utility of these objective measurements is that they guide the tester’s decision of when sufficient sweeps have been acquired to be able to categorise a stimulus level as showing a response or indicating response absence.

9.3. **Criteria for response presence**

For a CAEP to be categorised as present the following criteria should be met:

a) The response shall have an appropriate waveform morphology, amplitude and latency
b) The response shall be repeatable, as judged by similarity between replicates
c) The response morphology, amplitude and latency shall follow the expected trend of smaller amplitudes and longer latencies compared to responses obtained for a higher level stimulus, when available
d) The response shall have a sufficiently high SNR to satisfy the tester with a high degree of confidence that the “response” is genuine
If the equipment does not offer objective measurements\(^1\) the tester shall estimate the SNR visually. The following method is recommended: The “signal” is the size of the response, measured as the N1-P2 amplitude. In all but marginal cases it is usually sufficient to do this by eye, with reference to the vertical scale rather than using cursor measurements. The noise may be estimated from the average gap between a pair of optimally superimposed replicates, assessed across the entire timebase. This mirrors the method advocated by the BSA Recommended Procedure, where examples can be seen. Using this method, an SNR of 2.5 or more is usually associated with a p-value of 0.05 or less (for example see Figure 1); sufficient to conclude that the response is present, provided the other criteria have been satisfied.

There is no minimum response size requirement for response presence but in practice, responses smaller than 2.5 µV can rarely be distinguished from residual noise with confidence, even in good test conditions.

### 9.4. Criteria for response absence

For a CAEP to be categorised as absent the following criteria should be met:

a) There should be no likely response present; a possible response with an SNR less than that needed for response presence is not sufficient to qualify for response absence.

b) The residual noise in the grand average waveform shall be sufficiently low to be confident that a small response is not obscured by noise.

It is not sufficient to say “I can’t see a response”, the tester must have a high degree of confidence that a response is genuinely absent.

If the equipment does not offer an objective measurement of residual noise the tester shall estimate the residual noise visually, as above. The noise may be estimated from the average gap between a pair of optimally superimposed replicates, across the entire timebase. Using this method, residual noise of about 2 µV is usually low enough to provide the required degree of confidence that a response is genuinely absent. Systems reporting residual noise objectively may do so using a variety of algorithms; the reported value may differ across systems.

\(^1\) Fsp or related measurements designed for use in ABR detection are unsuited to cortical tests.
tester shall define what response absence noise criterion to use for their system.

Waveforms that do not meet the above criteria for response presence or response absence must be regarded as inconclusive and take no part in the definition of the CAEP threshold. Resolving inclusive levels normally require further averaging but occasionally, small or odd-looking responses remain inconclusive even after further averaging.

9.5. Definition of the CAEP threshold

The CAEP threshold is defined as the lowest level at which a response is present, with a response absent at a level of 10 dB or less below this level and a response present at 10 dB or less above this level.

It is sometimes sufficient to obtain responses down to a certain level without the need to obtain a formal threshold, for example if responses are recorded down to 20 dBHL. Such results should be described using the format ≤20 dBHL. Conversely if no response was recorded at any stimulus level up to, say, 100 dBHL, where response absence was demonstrated, the results should be described using the format >100 dBHL.

If a step size of 10 dB has been used the tester may, if desired, adopt an “interpolation” approach (Lightfoot & Kennedy 2006) in which the threshold may be reported as 5 dB below the lowest level at which a response is seen providing that response is larger than a specified amplitude (Lightfoot & Kennedy 2006 employed 5µV at and below 1 kHz and 3µV at higher frequencies); when smaller than the specified amplitude the threshold is taken as the level of the lowest response. When this interpolation technique is employed it shall be stated in the report, together with reference to the basis of the interpolation.

Note that replication is necessary to satisfy the criteria for response presence and response absence but replication may not always be needed for stimulus levels well above or well below threshold. The clarity of responses will guide the tester’s decision to replicate at such levels; where there is uncertainty, replication is helpful even for levels that do not contribute to the definition of threshold.
10. **Accuracy & Limitations**

There is an average difference between CAEP thresholds and the PTA thresholds in cooperative patients; this is known as a “bias” and is typically 5-10 dB (e.g. a figure of 6.5 dB has been reported (Lightfoot & Kennedy 2006)) with the CAEP threshold suggesting a slightly greater hearing loss than the PTA). The value of this bias will depend to some extent on the methods used for stimulus calibration, response acquisition and analysis and the presence of certain co-morbidities. It is technically valid to subtract the bias when predicting the PTA threshold but this subtraction shall be stated in the report and details given on how the bias was derived.

After subtracting any bias, there will be a spread of values in the CAEP – PTA difference in cooperative patients. After accounting for their 6.5 dB bias, Lightfoot & Kennedy (2006) found that 94% of threshold estimate differences were ≤±15 dB. Such information may allow a confidence range to be associated with CAEP results. However, the upper limit of the confidence range will not exceed the level of the CAEP threshold. Example: the above bias is rounded to 5 dB and a CAEP threshold of 50 dBHL is obtained. Subtracting the bias gives 45 dBHL as the best estimate of the PTA and there is 95% confidence that the PTA lies in the range 30 – 50 dBHL (45 - 15 and whichever is the lower of 45+15 or 50, in this case 50). More sophisticated corrections can be applied if they can be justified.

11. **Reporting**

A CAEP report should ideally include the following information:

- Hospital name and department
- To whom the report is addressed (e.g. doctor, care home staff, solicitor) including their reference if any
- Test date
- The patient’s name, date of birth and reference number
- Tester name
- CAEP threshold results in dBHL
- Confidence Intervals typical for the frequency/patient age (see above)
- Details of the test equipment used, including model & serial number
- The transducer types used
- The date of audiometric calibration of the equipment
• Notes on any issues that might have a bearing on the accuracy of the results

If an interpolation method has been used to arrive at the reported results this shall be stated. If any PTA-ERA bias has been subtracted from the CAEP thresholds to give a prediction of the PTA, this shall be stated including the value subtracted and its origin.

Table 1: Summary of basic stimulus and recording parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Montage</td>
<td>Cz +ve; Mastoid –ve; Fpz Gnd</td>
<td>Linked mastoids may reduce noise (unverified)</td>
</tr>
<tr>
<td>High Pass Filter</td>
<td>1 Hz</td>
<td></td>
</tr>
<tr>
<td>Low Pass Filter</td>
<td>15 Hz</td>
<td>30 Hz if 15 Hz is not available</td>
</tr>
<tr>
<td>Timebase/window</td>
<td>500 to 1000 ms</td>
<td>250 ms pre-stim is desirable</td>
</tr>
<tr>
<td>Stimulus type</td>
<td>Tone burst</td>
<td>Clicks, pips and speech tokens also work</td>
</tr>
<tr>
<td>Stimulus rise &amp; fall time</td>
<td>10 - 20 ms</td>
<td>Linear ramp</td>
</tr>
<tr>
<td>Stimulus plateau</td>
<td>30 - 200 ms</td>
<td>Only the first 30 - 50 ms evokes the response</td>
</tr>
<tr>
<td>Stimulus modality</td>
<td>Air or Bone conduction</td>
<td>Soundfield also possible</td>
</tr>
<tr>
<td>Stimulus calibration</td>
<td>As for audiometers</td>
<td>Only if using tone bursts</td>
</tr>
<tr>
<td>Number of sweeps</td>
<td>5 to 30 per sub-average</td>
<td>Depending on response size</td>
</tr>
<tr>
<td>Number of sub-averages</td>
<td>2 to 3</td>
<td>Sum to form a grand average</td>
</tr>
<tr>
<td>Repetition Rate (adults)</td>
<td>0.5 to 1.0 per second</td>
<td>Randomise if possible</td>
</tr>
<tr>
<td>Repetition Rate (older children)</td>
<td>0.25 to 0.5 per second</td>
<td>Randomise if possible</td>
</tr>
<tr>
<td>Display aspect ratio</td>
<td>100 ms = 5 µV</td>
<td></td>
</tr>
</tbody>
</table>
References


BS EN ISO, 389-1:- Acoustics. Reference zero for the calibration of audiometric equipment. Reference equivalent threshold sound pressure levels for pure tones and supra-aural earphones.


Ornitz, E.M. et al., 1967. The variability of the auditory averaged evoked response during


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Appendix 1: Supra-threshold CAEP testing in infants

Permanent childhood hearing loss (PCHL) is a potentially devastating long-term condition. Early intervention has the potential to reduce the negative impact of PCHL on the developing child. With the advent of new-born hearing screening programmes, the age that intervention commences has dramatically reduced. In England, for example, infants with a bilateral congenital moderate-to-severe PCHL are typically provided with hearing aids at a median age of 82 days (Wood et al. 2015).

The success of new-born screening has resulted in new challenges. For example, behavioural methods of hearing assessment cannot be used reliably until a developmental age of 7-9 months (Widen 1993). Therefore, when prescribing hearing aids to infants, clinicians rely on objective measurements of hearing threshold. The most commonly used measure is the frequency-specific ABR. The ABR is a well-established technique but it can be problematic for a variety of reasons:

- behavioural thresholds often deviate from predicted ABR thresholds by 10 dB, and occasionally by 20 dB (Stapells 2011; Stapells 2012).
- it may not be possible to detect an ABR when there is a severe hearing impairment, yet a hearing aid could still be beneficial (Stelmachowicz et al. 2008)
- middle-ear disease can complicate ABR detection (Stelmachowicz et al. 2008)
- an ABR is absent in some clinical populations e.g., auditory neuropathy (Roush et al. 2011)
- the ABR assesses hearing up to the brainstem and may miss disorders at a higher level in the brain

Although the observations of infant aided behaviour by parents and professionals are important (Bagatto et al. 2011), the range of observable behaviour in infants is limited (Bess & Humes 2003). Therefore, there is an urgent need to identify new procedures that can supplement existing practices by confirming the audibility of speech and the appropriateness of the hearing aid prescription in infants.

There are many reports in the literature that CAEPs can be recorded in adults and children with hearing loss while they wear their hearing aids (Rapin & Graziani 1967; Barnet 1971). In
some of these studies, the emphasis has been on confirmation of physiological detection of sound i.e., that sound is audible and is processed by the brain. In other studies, the focus has been on the ability to demonstrate physiological discrimination between sounds i.e., differences in the waveform evoked by two different stimuli (Korczak et al. 2005). The recent introduction of the HEARLab clinical system, developed by the National Acoustics Laboratories in Australia and Frye Electronics (USA), has increased interest in aided CAEPs. This system uses objective response scoring, based on Hotelling’s T² Statistic, to classify if there is a physiological response to the stimuli. More information can be obtained at http://hearlab.nal.gov.au/  

The morphology of the CAEP can vary considerably from one infant to the next, and is influenced by a number of factors including attention, arousal and recording parameters. In general, and in awake infants using slow stimulus repetition rates (0.5 to 1.0 /s), there is a prominent positive (upward) wave with a latency of around 150-250 ms. This will typically be preceded by a small negative component at around 80 ms and followed by a broad late negativity around 400 ms. Figure 2 shows the grand average CAEP obtained with the HEARLab system in a group of around 60 normal hearing infants, between 2-6 months of age, who were awake and alert during testing. This was obtained with the stimulus /g/ (duration 21 ms), extracted from a recording of uninterrupted dialogue, and presented in the sound field at a level of 65 dB SPL and at 0° azimuth.

For infant testing, a test environment suitable for visual reinforcement audiometry (VRA) is appropriate (BSA 2014). A single channel recording is recommended, with electrodes located as follows:

- Positive electrode: this electrode is placed in the midline of the scalp, usually close to Cz. While adult head topography graphs by Sussman et al. (2008) indicate that a little in front of Cz produces the highest signal, this is not possible in infants because of the location of the anterior fontanelle. A useful fall back option is to use a high forehead although unpublished evidence suggests that there may be a slight loss of SNR, necessitating a longer measurement time.

- Negative electrode: ipsilateral mastoid.

- Common electrode: contralateral mastoid or forehead.
CAEP obtained from a group of 60 normal hearing infants using the HEARLab system. This shows two sub-averages of around 75 sweeps in response to the stimulus /g/ (21 ms) presented at 65 dB SPL from a loudspeaker at 0° azimuth.

Detection of a CAEP depends on many factors including the behaviour of the infant at the time of testing. It is currently unclear what proportion of hearing-impaired infants fail to show a CAEP when the stimulus is audible. Two small-scale studies suggest this could be as high as around 33% (Chang et al. 2012; VanDun et al. 2012) although it is not clear if measurements were made under optimal recording conditions and with testers who were experienced in recording infants CAEPs.
Appendix 2: An example of CAEP testing of an adult medico-legal compensation claimant.

The claimant, a male in his late 50’s worked for 35 years in the textile industry. As he was a non-English speaker, his son acted as interpreter.

The claimant attended for CAEP testing, which at the hospital providing the service included tympanometry, 1 kHz ipsilateral reflex testing, conventional pure-tone audiometry in addition to 4-frequency air conduction CAEP hearing threshold estimation.

Results:
Tympanometry: normal bilaterally.
Ipsilateral 1 kHz Reflexes: equivocal on the right; ≤85 dBHL on the left.
Pure-tone audiometry is shown in figure 3. This did not correspond to an informal clinical assessment of the claimant’s hearing ability at interview.
CAEP thresholds are also shown in figure 3 and reveal thresholds that, whilst not normal, are substantially better than the audiogram suggest, with a configuration that is not characteristic of noise damage. Note that the “interpolation” approach (Lightfoot & Kennedy 2006) has been used when estimating the objective thresholds.

Figure 3
Pure-tone air conduction and corresponding CAEP estimated thresholds (#) of the claimant.
Figure 4 shows the CAEP averaged waveforms at 3 kHz. The pale grey waveforms are 3 sub-averages at each stimulus level whereas the bold coloured waveforms are the grand average of the 3 sub-averages. The system used offers a p-value and residual noise (RN) figure to assist interpretation. The p-value is derived from a combination of the cross correlation and signal to noise ratio of the waveforms, referenced to a data set of 1000 no-stimulus values. The testers used the response present (but using p ≤ .05) and response absent criteria suggested in this document.

**Figure 4**
CAEP waveforms for the 3 kHz tone burst stimulus. SWPS: sweeps used per grand average; N1: N1 peak latency; AMP: N1-P2 amplitude; CC: cross correlation coefficient; RN: residual noise based on the average gap between sub-averages; S/N signal to noise ratio, measured as the AMP/RN values. The vertical dotted line denotes stimulus onset. The CAEP threshold is 30 dBHL in both ears but is reported as 25 dBHL because the amplitude of the lowest present response is over 3 µV (the hospital adopts a criterion of 5 µV at and below frequencies of 1 kHz). EEG alpha activity is evident and sometimes (as in 40dB on the right) by chance the activity can be similar in sub-averages and so make response identification difficult. At 30dB,
chance works in our favour and the alpha activity differs across sub-averages so cancels in the grand average.

Appendix 3: An example of CAEP testing of an adult with learning difficulties.

Case background:
The patient was a female in her mid-thirties with Down Syndrome with severe intellectual impairment and non-verbal communication. Previous behavioural assessment using VRA suggested a brief turn to 60 dBA at 1 kHz. HaLD Speech Discrimination was 60% accurate responses to single words presented at 70 dBA.
Otoscopy revealed narrow ear canals, but was otherwise satisfactory.

CAEP Logistics:
The patient showed initial anxiety about the test and the room. A pre-test visit was arranged so the patient could explore the room and see the equipment before an appointment on another day for the CAEP.
Additional time was required to explain the test.
Time was spent introducing the electrodes and headphones to the patient.

CERA Thresholds:  
Left ear: 1 kHz ≤ 50dBNHL  3 kHz ≤ 60dBNHL  
Right ear: 1 kHz ≤ 60dBNHL  3 kHz ≤ 70dBNHL
Recommended Procedure
Cortical Auditory Evoked Potential Testing
BSA
2016
**Figure 5**
*CAEP waveforms for the 1kHz tone burst stimulus in an adult with learning difficulties.*

Note that the CAEP responses in Figure 5 are large; this is sometimes seen in adults with learning difficulties.

In this case the criteria for response absence were not met for stimuli below that where a response was present, so the CAEP results were reported using the “≤” qualifier. Clinical judgement was applied when using the results for management purposes.

Management: A hearing aid was fitted to the CAEP thresholds.

Outcomes: The patient's family and care team reported greater responsiveness to sound and increased vocalisations.