

www.CorticalERA.com

Welcome to the Cortical ERA Web Site

This is a non-profit educational & technical resource site for Audiologists to promote the development, availability and clinical use of Cortical electric response audiometry, a technique for objective threshold estimation based on the "N1-P2" response.

The impetus for creating this site is to:

- inform the international audiological community of the benefits and limitations of Cortical ERA;
- compensate for some misinformation on, or ignorance of, this subject in the literature;
- showcase a system designed by the author of the site to demonstrate how Cortical ERA can be implemented to produce a user-friendly, fast and efficient test (though the site's author has no interest in sales of equipment);
- generate sufficient user demand to persuade equipment manufacturers to provide an efficient version of this test available on their evoked potential systems.

The site's author is Guy Lightfoot, a Consultant Audiological Scientist in Liverpool, UK with a long-standing special interest in the subject. Your feedback on this site is welcomed.

Please Email comments, suggestions or queries to: G.Lightfoot@Liverpool.ac.uk

Disclaimer: Whilst every effort is made to provide correct information, the author cannot accept responsibility for errors of fact, omission or interpretation. The reader should understand that some content carries personal opinions.

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Background information on Cortical ERA

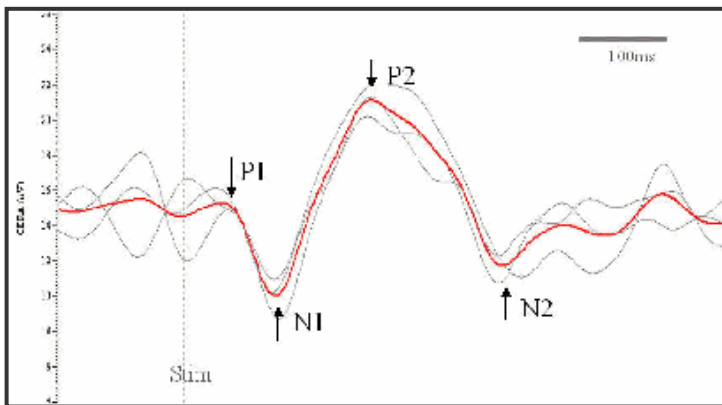
Electric Response Audiometry

ERA is actually an umbrella term for a collection of techniques in which electrical potentials are recorded, usually from the scalp of the subject, evoked by a sound stimulus. The presence of the response or the response characteristics allow us to infer conclusions about the subject's hearing ability or the performance of their auditory pathways. The original term was Evoked Response Audiometry until one bright spark pointed out that a behavioural response such as pressing a button was an "evoked response". The term Electric Response Audiometry has therefore been used. However, the International ERA Study Group have re-adopted the term "evoked" so as to embrace OAEs (which are evoked, but not electrical).

Historical Setting and other auditory evoked responses

The earliest report of relevance was that of Davis who identified the auditory cortical evoked response in 1939 although changes in the EEG evoked by a loud sound had been observed by Berger a decade earlier. Because Cortical ERA (CERA) was the first of the ERA techniques to find widespread clinical use (in the 1970s), the term ERA is sometimes used to refer to this particular technique. Confusingly, CERA is also known by a number of other terms: the N1-P2 response, slow vertex response (SVR) and the auditory cortical response (ACR). What is more, there are a number of other auditory-evoked responses that arise from the cortex, each having their own characteristics and clinical uses. They include CNV, MMN and P300. This web site makes no attempt to cover these other cortical responses. Also included under the umbrella of ERA are ECoChG, ABR and MLR.

What is the "N1-P2" response?



The N1-P2 response is one element of a larger series of events and arises in response to a change in auditory environment - it is also referred to as the acoustic change complex. In hearing threshold tests it is usually evoked by the onset of a tone, but it may be triggered by any abrupt change - in intensity, frequency etc. or even by the offset of a long tone. The N and P refer to the sign of the potential (negative and positive) at the vertex

compared to the potential at the reference electrode. Waveforms on this site are displayed "vertex positive up". For stimulus intensities well above threshold, N1 has a latency of about 100ms and P2 of about 200ms (you may see them referred to as N_{100} and P_{200}). As intensity is reduced towards threshold, the latencies increase to almost double these figures. The amplitude of the N1-P2 response may be up to about $25\mu\text{V}$ for moderate to high intensity stimuli, decreasing in size to zero at threshold. These relationships are referred to as input-output functions and knowledge of their characteristics helps us in evaluating an individual's hearing threshold. The generator of N1 is probably the primary auditory cortex but P2 probably has multiple generators, perhaps within the polysensory frontal areas.

Uses of the N1-P2 response

The main clinical application of this response is the objective estimation of the auditory hearing threshold. It may be most conveniently considered as the electrophysiological equivalent of the pure tone audiogram (PTA). The advantages, problems, acoustical constraints and audiological

considerations of the PTA are equally applicable to CERA with one important exception: the patient is not asked to play an active part in deciding whether to report that a stimulus has been heard. As such, CERA is most useful when the accuracy of PTA results are in doubt or are clearly erroneous, for example in cases of psychogenic or non-organic hearing loss. Patients with senility or learning difficulties also often yield inaccurate PTA results, yet are willing to offer the passive co-operation required for CERA. However, probably the largest client group is that with military, industrial or occupational hearing loss for whom any pension or compensation for their disability is linked or contingent on their hearing status. Even when the PTA results are accurate, CERA serves to remove all doubt over their validity and as such, can strengthen a claimant's case. The utility of Cortical ERA in the above contexts is well established (Coles & Mason, 1984; Hyde et al, 1986; Alberti et al, 1987; Prasher et al, 1993; Hyde, 1997; Tsu et al, 2002; Cone-Wesson & Wunderlich, 2003; Hone et al, 2003). The Cortical ERA service in Liverpool has undertaken tests on over 9,000 patients / medico-legal claimants since its introduction 20 years ago and the technique is accepted by the British legal system as the definitive test of hearing status.

Cortical ERA has a major limitation of application: it is based on the N1-P2 response which does not mature fully until the patient's late teens (Stapells, 2002). It is therefore widely regarded as an adult threshold estimation test although it is still a viable test for children as young as about 8 years old. In these older children, the immature response has a different morphology, with N2 & P3 often being more dominant and perhaps because of this, a longer inter-stimulus interval (slower repetition rate) is necessary to record a satisfactory response. However, some audiologists claim to have used CERA with success in 2-3 year olds, though there is insufficient data in the literature to substantiate this. Although it has no direct neurological application, CERA may be used as an adjunct to other assessment tools to assist in the diagnosis of retro-cochlear pathology. For example, the combination of clear OAEs, normal ABR and an absent CERA can occur in cortical deafness. An absent ABR and recordable CERA responses can be seen in many cases of auditory neuropathy or desynchrony. There is good evidence (Hyde, 1997; Martin & Boothroyd, 1999; Cone-Wesson & Wunderlich 2003) that the N1-P2 response can also be used to access features of auditory discrimination and central auditory processing.

Accuracy of threshold estimation

If the test parameters and protocol are chosen with care (see later), the N1-P2 response is capable of estimating the true hearing threshold of adults with a degree of accuracy at least as good as that of the ABR - within 10dB in most cases (Hyde, 1986; Tsu, 2002). A study in Liverpool using the author's original system suggested a mean Cortical ERA - PTA difference of 4dB. There have been reports that the accuracy of this technique is poor, but it is possible that inappropriate parameters or methodology are responsible. Subject factors are known to influence accuracy. The morphology and amplitude of the N1-P2 complex is degraded with drowsiness and in particular, in the different stages of sleep and although N1 is larger if the subject actively attends to the stimulus, it is sufficient that the patient remains generally alert. Requiring them to quietly read a magazine is ideal. Drugs known to induce drowsiness are to be avoided (sedatives, alcohol etc). Nevertheless, there is a small percentage of individuals in whom, for no apparent reason, error in the threshold estimate exceeds 20dB (Albera et al, 1991). Ironically, and to our advantage, the quality and size of the N1-P2 response is often better in cases of non-organic hearing loss than in honest subjects. This author believes that this is an unintended attention effect: the stimuli may be of less interest to the honest subject than the malingerer, whose attention is irresistibly drawn to the sounds, particularly those at an intensity below their volunteered threshold yet still audible. Indeed, in some individuals, a larger response is seen at, say, 10dBSL (sensation level) than at 40dBSL, the higher intensity posing less of a "threat" since it is above their volunteered hearing threshold. As with other ERA techniques (e.g. the ABR), CERA accuracy is better in cases of cochlear hearing loss than in normal subjects: the loudness recruitment associated

with cochlear loss compresses the transition between hearing and not hearing into a narrower intensity range, thus making the input-output function steeper.

Methodology

A table below summarises the test parameters.

The electrode montage used for the N1-P2 cortical response is a Cz (vertex) /mastoid electrode pair. Some loss of response amplitude occurs if a high forehead site is chosen instead of Cz (Vaughan & Ritter, 1970). Either mastoid can be used as the reference site, regardless of test ear and indeed, a slight ($\sqrt{2}$) reduction in myogenic activity can be achieved by using a linked mastoid arrangement. By convention, a forehead ground is used.

The filter settings (recording bandwidth) depend, of course, on the spectral peak of the N1-P2 response which lies in the range 2 to 5 Hz. Since we are interested in response detection (rather than analysis), a narrow filter bandwidth helps achieve good signal to noise ratio and is optimally 1 Hz to about 15 Hz (30 Hz can be used if this is the lowest available low-pass setting).

The analysis epoch (time base or window) can be in the range 500 to 1000 ms. It is useful to include a pre-stimulus epoch of about 250 ms to assist in the assessment of background activity. As with other ERA tests, it is important to duplicate or triplicate the response, particularly when the response is small, close to threshold.

Although a click or tone pip may be used, the stimulus of choice is a tone burst of the desired audiometric frequency. The response can be detected at all audiometric frequencies although at frequencies above 2kHz, a smaller response is recorded and so the precision of the threshold estimate is probably poorer. The frequency specificity of this stimulus, and of the response it evokes, is almost ideal and far better than that afforded by tone pips used in ABR tests. This is simply a by-product of the number of cycles in the stimulus. The rise time of the tone burst is an important parameter. If this was very short (if we were to abruptly present the tone burst without a gradual rise time) then we would suffer from a loss of frequency specificity which may be important in steeply sloping or notched audiograms. However, the amplitude of the cortical response diminishes if long rise and fall times are used. A good compromise is to have a linear rise time of 10 to 20 cycles (e.g. 10 ms at 1 kHz). The "plateau" of the tone burst also needs to be defined. Very brief plateaus (<25ms) would compromise frequency specificity and also affect the loudness of the stimulus through the process of temporal integration and hence diminish the response (Davis & Zerlin, 1966; Skinner & Jones, 1968). After the first 30-50ms of the stimulus, the response has been evoked, so there is little merit in extending a plateau for much longer than this. Interestingly, many centres use tone bursts of 100 ms or more. Very long tone bursts should be avoided, since the end of the tone burst will also evoke a cortical "off response" as well as slightly and unnecessarily extending the test time. Those centres using long plateau times will argue that they do so in order to intentionally separate the on and off responses. A plateau of 100 ms (often advocated) should be avoided since in theory, this can cause the destructive overlapping of the onset P2 and offset N1 responses. In practice, these arguments are rather academic and a plateau of either about 50 ms or 200ms is acceptable. A stimulus of this duration allows us to use the calibration reference values available for pure tone audiometry since the extent of temporal integration is small enough to ignore. This is a great practical advantage over the brief stimuli used in ABR for which there is still no agreed calibration values, and it is of particular importance in the medico-legal context.

The choice of stimulus repetition rate is critical and represents a compromise between two opposing considerations. On the one hand, we would like to make the rate fast to shorten the test time, especially if we have several frequencies to test. On the other hand, we do not want to degrade the response and so make its identification difficult. A reasonable question to ask is "what is the maximum rate that does not degrade (reduce the amplitude) of the response?". To record a response unaffected by rate effects, we need to keep the rate down to about one stimulus every ten seconds, i.e. 0.1Hz (Appleby, 1964;

Davis et al, 1966). Using a rate this slow would make the test very time consuming. Although rates above 0.1Hz diminish the response, the rate that yields the best signal to noise ratio improvement per unit test time is chosen. For cortical responses in adults it is normal to have a repetition rate between 0.5 and 1.0 stimuli per second (1 - 2 seconds between stimuli) (Rapin, 1964; Davis & Zerlin, 1966). In older children 0.25 to 0.5 Hz (2 – 4s between stimuli) is required. At these rates we record a partially adapted response but we do so in a reasonable time. Of course the very first stimulus in an averaging run is un-adapted because it is preceded by silence and is therefore large. The second is somewhat adapted and the third is more so. The amplitude continues to diminish slightly during the average, though the biggest change is at the start of the averaging run (Walter, 1964; Ozesmi et al, 2000).

The above feature plays a part in our choice of the number of sweeps in an average. A very common mistake is to over-average. Averages containing more than 50 sweeps (used to further improve the signal to noise ratio) are often counter-productive, and merely serve to further adapt the response (Henry & Teas, 1968). The number of stimuli required to produce an acceptable response depends upon the size of the response. Stimuli above about 20 dBSL usually produce a clear response after 20 or so stimuli whereas closer to threshold, 30 to 50 stimuli may be required. Replication is essential and for greatest efficiency, the above numbers of sweeps should be distributed across several sub-averages and then combined to form a grand average (e.g. 30 sweeps in total, 10 sweeps in each of 3 sub-averages).

Another way of enhancing response detection is to use a non-rhythmical stimulus and some systems provide the facility for a pseudo-random stimulus rate. This facility used to be common on systems 20 years ago but few systems offer it now - so much for progress! This is also useful in prolonged testing sessions where the response amplitude diminishes due to habituation - a process which can be in part reduced by making the stimulus less predictable (Rapin, 1964; Rothman et al, 1970). Other tactics may involve randomising other aspects of the stimulus, for example the ear under test (Butler, 1972), test frequency or test intensity. Giving the patient a brief break or making them more alert in some other (devious?) way can rejuvenate a flagging response.

Parameter	Value	Comment
Electrode Montage	Cz +ve; Mastoid –ve; Fpz Gnd	Linked mastoids may be used
High Pass Filter	1 Hz	
Low Pass Filter	15 Hz	30 Hz if 15 Hz unavailable
Epoch / time base	500 to 1000 ms	250 ms of pre-stim preferred
Stimulus type	Tone burst	Clicks & pips also work fine
Stimulus rise & fall time	10-20 ms	Linear ramp
Stimulus plateau	About 50 ms or 200 ms	Avoid 100 ms
Stimulus modality	Air or Bone conduction	
Stimulus calibration	As for audiometers	Only if using tone bursts
Number of sweeps/trials	5 to 20 per sub-average	Depending on response size
Number of sub-averages	2 to 3	Sum to form grand average
Repetition Rate (adults)	0.5 to 1.0 /s (ISI =1–2 s)	Randomise if possible
Repetition Rate (older children)	0.25 to 0.5 /s (ISI =2–4 s)	Randomise if possible

Below is a summary of the main early papers upon which the choices for test parameters are based. Many parameters are a compromise between conflicting requirements.

Stimulus rise time: A shorter rise time produces a larger response. (Skinner & Jones 1968). Too short a rise time makes the stimulus less frequency specific. Optimum rise time ~10 - 20 ms.

Stimulus duration (plateau): Maximum response seen with durations between 25-50ms. (Davis & Zerlin 1966), (Skinner & Jones 1968). A duration of about 100ms can cause onset & offset responses to destructively interfere. Duration > 200ms induces unnecessarily habituation and prolongs test time.

Number of sweeps (stimuli) per average: Response amplitude declines during each averaging run. Use as few as possible because of diminishing return of signal-to-noise improvement (Walter 1964). Fewer stimuli reduces adaptation. (Henry & Teas 1968).

Stimulus repetition rate: Over 10s between stimuli required to avoid any adaptation effects. (Appleby 1964), (Davis et al 1966). Optimum rate for test is 0.5 – 1.0 Hz (Rapin 1964), (Davis & Zerlin 1966).

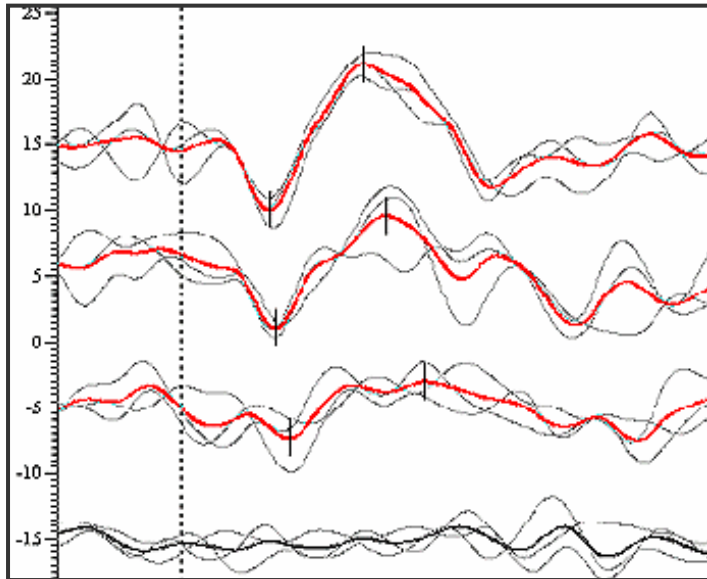
Stimulus randomisation: Randomisation increases amplitude and reduces adaptation (Rapin 1964), (Rothman, Davis & Hay 1970). Amplitude increased if presentation side is randomised (Butler 1972).

Test session duration: Poorer responses are recorded after 30 minutes (Roeser & Price 1969).

Electrode site: Vertex (Cz) gives optimal amplitude (Davis & Zerlin 1966). Amplitude at high forehead is only 60% of vertex amplitude (Vaughan & Ritter 1970).

Procedure: With most candidates considered for CERA testing where non-organic hearing loss is suspected, it is worth explaining first what tests will be conducted: the Author's routine is to include tympanometry with acoustic reflexes, pure tone audiometry then CERA (described as the automatic version of the PTA). One then often finds that an accurate PTA is provided, especially if the PTA method is adapted to minimise non-organic overlay (see Cooper & Lightfoot, for example). For CERA, the patient is required to give their passive co-operation and comply with normal electrode attachment procedures. As with conventional pure tone audiometry, the patient is seated in a standard audiometric room, wearing earphones and is asked to remain quiet and awake. They should be encouraged to read a magazine or book for the duration of the test. The patient should be monitored (close circuit TV & intercom) and re-instructed if they become drowsy, close their eyes or attempt to disrupt the test. Physical relaxation (as required for ABR & steady-state tests) is not necessary and could be counter-productive.

The procedure for the estimation of the hearing threshold at a given frequency is essentially the same as that used in conventional audiometry - obtain a definite, supra-threshold response and repeat trials at progressively lower intensities until the threshold has been established, using a bracketing technique. To minimise test time however, a 20dB down, 10dB up procedure is advantageous (steps that are twice as coarse as in behavioural audiometry), similar to the procedure often adopted in threshold ABR tests. The chosen threshold is the result of an analysis of the size and latency of the lowest intensity positive response. An interpolation to the nearest 5dB is possible even though a minimum step size is 10dB, hence the term threshold estimation. An agreed interpolation rule is necessary. The author uses a 5 μ V amplitude criterion (3 μ V at 3 kHz and above): if the response is less than this, that is the threshold intensity; if greater, the threshold is 5 dB lower.



Here is an example of 500 Hz responses obtained at 40, 20, 10 (taken as threshold) and 0 dBHL. The time base extends from 250 ms prior to the stimulus (dashed line) to 650 after the stimulus onset. Three sub-averages are shown superimposed with their grand average (in red, since this is a right ear test). The N1 trough and P2 peak (displayed "vertex positive up") are marked. Collecting the data into sub-averages helps in response identification. Note how there is considerable residual "noise" in the sub-averages. They contain only five sweeps each. Traditionally evaluating the threshold is by subjective assessment but the same objective

scoring techniques used in the ABR can be applied to this response.

The choice of the initial test intensity should be made without reference to any existing results from the patient's previous behavioural tests, in order to ensure tester objectivity. A fixed intensity (e.g. 60dBHL) is most appropriate. In cases where a protracted test session is envisaged (as in some medico-legal tests where results at four or more frequencies have been requested), the first threshold to be obtained will give us an approximate idea of the accuracy of a previously obtained audiogram. From this it may be possible to start each new frequency at, say, 20 to 30dB above the predicted true threshold, thus saving test time by avoiding unnecessary supra-threshold trials. However, some users prefer to retain full scientific objectivity by performing CERA tests blind to any other results.

Masking considerations

As with all audiological tests, we need to consider masking, and the basis of masking in these tests is the same as that used in conventional pure tone audiometry. We do not have the luxury of being able to find the plateau of the masking function so we must calculate the desired masking intensity:

$$I_m = I_s - TTL + 10 + ABG_{nt} \quad \text{where:}$$

- I_m is the masking intensity (calibrated to normal audiometric masking standards),
- I_s is the stimulus intensity (calibrated to normal audiometric pure tone standards),
- TTL is the minimum transcranial transmission loss (inter-aural attenuation) associated with the transducer (e.g. 40dB for TDH series earphones)
- ABG_{nt} is the air-bone gap in the non-test ear at the test frequency.

In the client groups for whom CERA is most useful, we often do not know ABGnt so an educated guess is required, based on available information.

One common problem with the design of most ERA equipment is that manufacturers frequently provide only wide band noise for masking purposes, but if narrow band noise is available then this should obviously be used.

Optimizing the test protocol for Cortical ERA

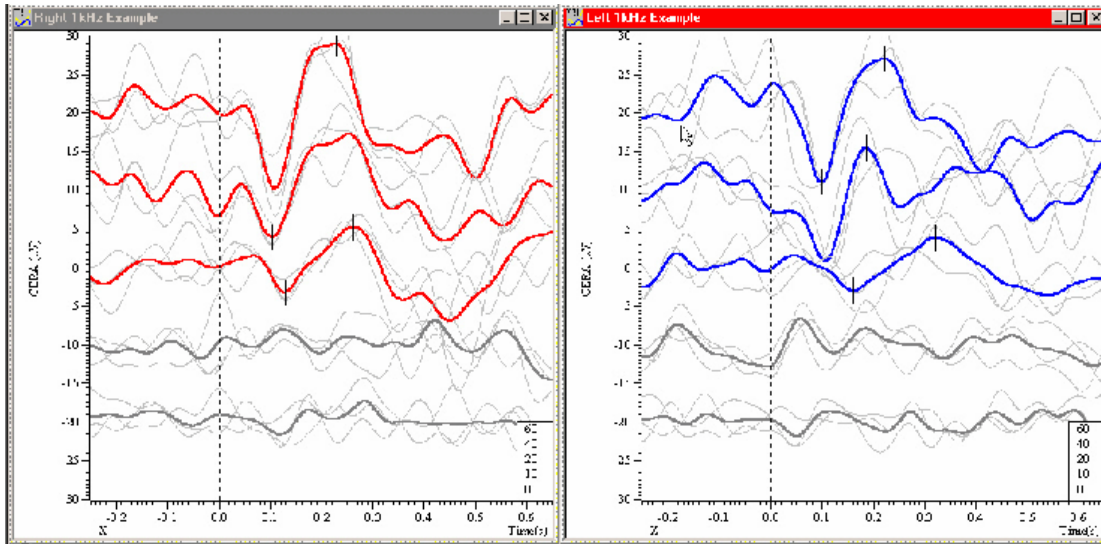
There are two main practical problems with the clinical application of Cortical ERA on conventional ERA systems that can be improved by appropriately designed software:

1. The manual manipulation of waveforms (combining & superimposing sub-averages and the creation of intensity series are examples) and other predictable tasks are both tedious and time consuming.
2. Long test sessions, especially using a predictable stimulus, lead to a diminution of the response, degrading accuracy and even further extending test time.

The test can be improved in terms of ease of use, speed and accuracy by addressing these issues. The most obvious and productive measure is to **automate all predictable tasks** normally undertaken by the operator.

Other components of an efficient Cortical ERA system (as implemented in the author's system) include:

- Pseudo-alternate binaural stimulation. In order to disrupt the monotonous predictable stimulus normally used in averaging, both ears may be tested using a P300-like oddball paradigm but where right and left ears are the "rare" and "frequent", and have equal likelihood. This random presentation is very "attention-grabbing" and difficult to ignore, slowing the habituation process somewhat. It is also efficient in that the user interaction required to assess the waveforms and select the next test intensity is less than twice that required in monaural tests. The intensities may differ for each ear, though this form of averaging is not appropriate if masking is required to prevent cross-hearing.
- Non-rhythmical stimulus presentation. A further measure that may be applied in an attempt to arrest the decline in response magnitude and to make the stimulus less monotonous is to introduce some variability into the stimulus repetition rate. A mean value of 0.7 Hz with 30 % variability is recommended but a slower rate with greater variability is sometimes helpful in patients with a poor quality or small N1-P2 response.
- Automatic per-stimulus replication. To assess response status, replicates are needed. Rather than manually recording several averages consecutively (which may differ as the patient's arousal level or myogenic status changes) 3 replicates are constructed pseudo-simultaneously. The 3 sub-averages A, B & C each receive an evoked response sweep in turn (ABCABC etc) until 15 stimuli have been delivered (5 into each sub-average). A grand average (red for right, blue for left) is then computed and the 4 averages are superimposed for operator subjective visual assessment. Further sets of 15 stimuli may be delivered for near-threshold or indistinct responses, but a 10s stimulus-free period is given before the averaging resumes to allow the response to recover. These processes are automatic and therefore fast, requiring no laborious waveform manipulation.
- Digital filtering of individual sweeps *prior* to averaging is possible when very fast processing is available.
- Automatic cursor placement on N1 & P2 within pre-set latency limits speeds waveform assessment.
- Cross-correlation of the 3 sub-averages within a fixed or cursor-related latency range is a basic form of machine scoring and assists user-assessment.
- Automatic intensity sorting of waveforms when viewing an "intensity series" obviates laborious and time consuming manual waveform manipulation. The waveforms below (suggesting a 10 dBHL threshold in both ears) were acquired and analysed in 6 minutes.



- Continual display of the ongoing EEG assists identification of excess EEG alpha and myogenic activity. In addition to the usual artefact rejection, a manual pause facility that withdraws the stimulus carries two benefits: (a) the user can use this means to introduce greater variability in the stimulus when required, and (b) when the test is paused because the patient is restless or noisy, unexploited stimuli do not habituate the response whilst waiting to resume averaging.

Note that no single feature detailed above is crucial for successful N1-P2 recording but together they combine to enhance speed, precision and ease of use.

Want to run an optimised test yourself? There are some video files you can view to see all of the above features in action. In fact, see the actual waveforms in the above figure being collected. Go to www.CorticalERA.com, select the Downloads page and take a look.

Speed

One of the chief practical problems with Cortical ERA is that of test time. In order to take advantage of the superb frequency specificity of the test, one is frequently asked to re-construct a major portion of the audiogram. For example, in medico-legal cases, there is a requirement to obtain threshold estimates at those frequencies used in the calculation of disability (typically 3 or 4 frequencies in both ears by air conduction). In addition, issues of causation make the objective identification of an acoustic "notch" attractive, requiring 6kHz and 8kHz. Bone conduction tests, with masking, may be needed at one or more frequencies. Test session can therefore become protracted. Since the response declines over time, this poses a very serious issue and if standard equipment is used, it is not uncommon for patients to have their tests split over two sessions if a comprehensive range of tests is sought.

Conventional CERA (that is, performed on a standard auditory evoked potential system) typically takes about 90 minutes for 8 thresholds (Hyde, 1997).

Using the author's "optimized" Cortical ERA system, in tests on 56 patients upon whom air conduction thresholds were estimated in both ears at between 3 and 6 frequencies, the average time taken to establish each threshold was 3.2 minutes using typically 3–5 intensities. Most 4-frequency, 2-ear air conduction tests took about 30 minutes. This is the "earphone on" time.

Clearly, additional time is needed for electrode attachment, interview, otoscopy, tympanometry etc. Nevertheless, the test time with this system is substantially less than that using a conventional system. Since the response degrades with time, a faster test is likely to yield somewhat better accuracy.

Ease of use

This is one of the other benefits of an optimized system, since almost all of the mundane aspects of user interaction are removed, the software calling for tester involvement only when judging a response or specifying the next test intensity etc. Audiologists experienced in Cortical ERA on conventional equipment have been most impressed with the simplicity and ease of use of a system developed specifically for this application.

Other design features of the system

In addition to the pseudo-simultaneous bilateral air conduction cortical ERA threshold test, I have included the following features to make it a comprehensive clinical and research tool:

- A monaural air conduction cortical ERA threshold test with contralateral narrow band masking
- A bone conduction cortical ERA threshold test with contralateral narrow band masking
- A user-friendly daily subjective calibration check program to ensure correct system function
- A program to facilitate periodic objective stimulus calibration using standard audiological calibration equipment
- A "review" facility to allow previously recorded waveforms to be viewed and printed off-line
- Full user control of all major test parameters within sensible limits
- Provision to create and employ non-standard stimulus waveforms for research purposes

Implementation

Since there is no currently available evoked potential system with full programming capabilities (unlike the old Nicolet Pathfinder), this system was developed from scratch using the following elements:

- A standard desktop personal computer
- A clinical audiometer (Interacoustics AC30) operating under RS232 control from the computer to provide stimulus attenuation & routing together with narrow band noise
- Cambridge Electronic Design hardware and software:
 - CED 1902 isolated low-noise EEG amplifier
 - CED Power (or Micro mk II) 1401 signal processor
 - CED Signal software (running specially written scripts)

Whilst this system is available, this is NOT a hard-sell exercise and the author would like to see similar software developed by the existing ERA system manufacturers. Please see the "take home message" on the Downloads page. Bringing the potential (ha ha!) of this test, especially in "optimized" form, to the attention of the international Audiological community is the primary aim. It seems a great pity that such a useful audiological tool has hitherto been overlooked by many and under-developed by all.

Sermon over! If you have read this far then thank you for your interest.

Still curious? Have a look at the ABR-v-CERA page to compare the two methods.

Please feedback any comments you may have to G.Lightfoot@Liverpool.ac.uk

A comparison of ABR & Cortical ERA as threshold estimation tests

Since both the auditory brainstem response (ABR) and Cortical ERA can be used for threshold estimation, it is worth briefly highlighting the pros and cons of the two techniques.

ABR responses are generally less variable, more robust and essentially immune from the patient's mental state and can conveniently be recorded in sleep, under general anaesthesia or with the patient physically relaxed. However, the presence of excess myogenic (muscle) activity makes accurate threshold estimation unlikely. Cortical ERA tests are much less sensitive to muscle activity but are affected by mental arousal level, making them most suitable for alert adults and passively co-operative older children. ABR tests require short duration stimuli which carry restricted frequency-specific information and makes low frequency tests especially difficult whereas cortical tests can use longer, highly frequency-specific stimuli, allowing an audiogram to be constructed, assuming one has the time and inclination to do so.

The following table summarises the main pros & cons of the two tests as implemented on a **standard** ERA system (manual collection & manipulation of data):

Issue	ABR	Cortical ERA
Age of patient	All ages	Adults & children >8 years
Requirements of patient	Low muscle activity	Reasonably alert
Patient Conditioning	Lying down, eyes closed, relaxed	Sitting, reading or watching a video
Frequency Specificity	Using clicks: almost none Using tone pips: about 30dB per octave maximum audiogram slope	Almost ideal, capable of resolving audiometric notches
Frequency range	1 - 8 kHz; 500 Hz with difficulty	250 - 8000 Hz
Accuracy of threshold in individuals	Clicks: typically ± 10 dB Pips: depends on frequency: 10-15dB at 2 - 4 kHz; increasingly worse at lower frequencies	Typically ± 10 dB Accuracy is poorer in a small (~5%) percentage of cases
Typical test duration (assuming 3-5 levels)	8-10 minutes per threshold	8-12 minutes per threshold
Calibration of Stimuli	No agreed international standard	Uses international audiometric pure tone standards
Equipment Requirements	Standard ERA system Better & quicker with specialised software	Standard ERA system Better & quicker with specialised software

Both techniques require waveform replication at each intensity, creation of grand averages, sorting of waveforms into intensity order, cursor placement, and should ideally include objective waveform scoring (response evaluation). Such software is becoming available for ABR-based tests, driven primarily by the time constraints inherent in the testing of neonates. The "optimized" Cortical ERA test described on this site in an example of similar software, but which has yet to be implemented on a standard ERA platform.

Summary of ABR -v- Cortical ERA comparison

The two techniques are similar in many respects (test time and accuracy of threshold prediction) yet offer different advantages and limitations. ABR can be used in neonates and young children; Cortical ERA is highly frequency specific, allows testing down to low frequencies, accesses a greater portion of the auditory pathway and uses formally acknowledged calibration reference data. Perhaps the situation is best summarised by Stapells (2002): Cortical ERA is "the (threshold estimation) measure of choice for most older children and adults". "It is unfortunate that especially in the United States, the P1-N1-P2 slow cortical response is underused, having been replaced by the ABR".

Just a very brief note here on the emerging use of Steady-State techniques: the pros & cons appear very similar to those of the ABR but with (possibly) better frequency specificity and better developed objective assessment tools. However, Steady-State techniques have an even more stringent requirement for patient relaxation than does ABR and thus a greater degree of patient co-operation is needed. This may limit its utility in non-organic and medico-legal client groups.

The Literature on Cortical ERA

Selected research papers

Most of the original spadework on Cortical ERA was undertaken in the 1960s & 1970s (before the auditory brainstem response became the "hot" topic and diverted everyone's interest!) so much of the literature is quite old. The following list is by no means exhaustive and mainly reflects this author's subjects of interest within this field.

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Antinoro, F. & Skinner, P.H. 1968. The effects of frequency on the auditory evoked response. J Aud Res, 8, 119-123.

Appleby S. 1964. The slow vertex maximal sound evoked response in infants. Acta Otol (suppl) 206: 146-152

Bourbon, W.T., Will, K.W., Gary, H.E. & Papanicolaou, A.C. 1987. Habituation of auditory event-related potentials: a comparison of self-initiated and automated stimulus trains. Electroenceph Clin Neurophysiol, 66, 160-166.

Butler R. 1972. The influence of spatial separation of sound sources on the auditory evoked response. Neuropsychologia. 10(2): 219-226

Coles RRA & Mason SM. 1984. The results of cortical electric response auditory in medic-legal investigations. Br J Audiol. 18: 71-78

Cone-Wesson B & Wunderlich J. 2003. Auditory evoked potentials from the cortex: auditory applications. Curr Opin Otolaryngol Head Neck Surg. 11(5): 372-377

Davis H & Zerlin S. 1966. Acoustic relations of the human vertex potential. J Acous Soc Am. 39:109-116

Davis H., Mast T., Yoshie N. & Zerlin S. 1966. The slow response of the human cortex to auditory stimuli: recovery process. Electroenceph Clin Neurophysiol 21:105-113

Henry G & Teas D. 1968. Averaged evoked responses and loudness: analysis of response estimates. J Speech Hear Res. 11(2): 334-342

Hone SW, Norman G, Keogh I & Kelly V. 2003. The use of cortical evoked response audiometry in the assessment of noise-induced hearing loss. Otolaryngol Head Neck Surg 128: 257-262

Hoth, S. 1993. Computer-aided hearing threshold determination from cortical auditory evoked potentials. Scand Audio,. 22(3), 165-177.

Hyde M, Alberti P, Matsumoto N & Li YL. 1986. Auditory evoked potentials in audiometric assessment of compensation and medicolegal patients. Ann Otol Rhinol Laryngol. 96: 514-519

Hyde M. 1997. The N1 response and its applications. Audiol Neurootol. 2(5): 281-307

Lammertmann, C., Fujiki, B., Lütkenhöner, B. & Hari, R. Short-term decrement of the auditory N1m response. In Biomag2000, Proc. 12th Int. Conf. on Biomagnetism. Eds. J Nenonen, RJ Ilmoniemi, T Katila, pp. 50-53. Espoo, Finland: Helsinki University of Technology.

- Lightfoot G. & Horseman G. 2003. *Optimising the N1-P2 adult threshold estimation test. XVIIIth Biennial Symposium of the International ERA Study Group, Puerto de la Cruz, Tenerife, June 2003.*
- Martin BA & Boothroyd A. 1999. *Cortical, auditory, event-related potentials in response to periodic and aperiodic stimuli with the same spectral envelope. Ear Hear. 20(1): 33-44*
- McCandless, G.A. & Best, L. 1964. *Evoked responses to auditory stimuli in man using a summing computer. J Speech Hear Res, 7, 193-202.*
- Nelson, D.A., Lassman, F.M. & Hoel, R.L. 1969. *The effects of variable-interval and fixed-interval signal presentation schedules on the auditory evoked response. J Speech Hear Res, 12(1), 199-209.*
- Ozesmi C, Dolu N, Suer C, Golgeli A & Ascioğlu M. 2000. *Habituation of the auditory evoked potential in a short interstimulus interval paradigm. Int J Neurosci. 105(1-4): 87-95*
- Pantev C, Eulitz C, Hampson S, Ross B & Roberts LE. 1996. *The auditory evoked "off" response: sources and comparisons with the "on" and "sustained" responses. Ear Hear. 17(3): 255-265*
- Polich, J., Aung, M. & Dalessio, D.J. 1988. *Long latency auditory evoked potentials: intensity, inter-stimulus interval and habituation. Pavlov J Bio. Sc,i 23, 35-40.*
- Prasher D, Mula M & Luxon L. 1993. *Cortical evoked potential criteria in the objective assessment of auditory threshold: a comparison of noise induced hearing loss with Meniere's disease. J Laryngol Otol. 107(9): 780-786*
- Prosser, S., Arslan, W. & Michelini, S. 1981. *Habituation and rate effect in the auditory cortical potentials evoked by trains of stimuli. Arch Otorhinolaryngol, 233, 179-187.*
- Rapin I. 1964. *Practical considerations in using the evoked potential technique in audiometry. Acta Otol (suppl) 206: 117-122*
- Roeser R & Price L. 1969. *Effects of habituation on the auditory evoked response. J Aud Res. 9(4): 306-313*
- Rothman H, Davis H & Hay I. 1970. *Slow evoked cortical potentials and temporal features of stimulation. Electroenceph Clin Neurophysiol. 29(3): 225-232*
- Skinner P & Jones HC. 1968. *Effects of signal duration and rise time on the auditory evoked potential. J Speech Hear Res. 11(2): 301-306*
- Stappels, D. 2002. *Cortical event-related potentials to auditory stimuli. In: Katz J. Handbook of Clinical Audiology_(5th Ed). Lippincott Williams & Wilkins. ISBN 0-683-30765-7.*
- Tsu B, Wong LL & Wong EC. 2002. *Accuracy of cortical evoked response audiometry in the identification of non-organic hearing loss. Int J Audiol. 41(6): 330-333*
- Vaughan H & Ritter W. 1970. *The sources of auditory evoked response recorded from the human scalp. Electroenceph Clin Neurophysiol. 28(4): 360-367*
- Walter WG. 1964. *Retrospective summary of definitive tests for hearing in young children. Acta Otol. (suppl) 206: 162-172*
- Woods, D.L. & Elmasian, R. 1986. *The habituation of event-related potentials to speech sounds and tones. Electroenceph Clin Neurophysiol, 65, 447-459.*

The following is a list of text books relating to this topic, some old and out of print, others more recent. In the personal opinion of this enthusiast, some have got it **right whilst**

others, for a variety of reasons, have **not**. My comments are *in italics*; Authors' quotes are "in parentheses".

Dobie RA. Medical-Legal Evaluation of Hearing Loss. (2nd Ed). Singular, 2001. ISBN 0-7693-0052-9.

Standard reference text on the subject. Included here because of the author's comment on the slow vertex response (cortical ERA): "This appears to be an uncommonly sensitive test which has been surprisingly little-used in the United States."

Gibson WPR. Essentials of Clinical Electric Response Audiometry. Churchill Livingstone, 1978. ISBN 0 443 01322 5.

A superb and comprehensive text on ERA methods of the late 1970s. The original "ERA bible" for many (older!) ERA practitioners.

Hall JW III. Handbook of Auditory Evoked Responses. Allyn & Bacon, 1992. ISBN 0-205-13566-8.

An excellent review of material up to the early 1990s.

"For threshold estimation in malingering patients, recording the AMLR (middle latency) with tone-burst stimuli is the most precise and accurate AER available for clinical use." I disagree with this statement. The N1-P2 slow vertex response / Cortical ERA is not really considered here as a threshold estimation tool, Hall's choice being between the ABR and AMLR.

Hall JW III & Mueller HG III. Audiologists' Desk Reference Vol 1. Singular, 1997. ISBN 1-56593-269-2. Cortical ERA requires passive co-operation "...but if patients are so cooperative why not just perform behavioral audiometry?" ABR also requires passive co-operation!

Katz J. Handbook of Clinical Audiology (5th Ed). Lippincott Williams & Wilkins, 2002. ISBN 0-683-30765-7. Chapter by David Stapells:

A comprehensive and authoritative review. The P1-N1-P2 response is "the (threshold estimation) measure of choice for most older children and adults". "It is unfortunate that especially in the United States, the P1-N1-P2 slow cortical response is underused, having been replaced by the ABR".

McPherson DL. Late Potentials of the Auditory System. Singular, 1996. ISBN 1-56593-163-7.

Only one page of this book on long latency evoked potentials deals with the N1-P2 response as a threshold estimation tool. The author states that long latency eps are "not well suited for determination of hearing sensitivity". However, a table of test parameters suggests values that would be wholly inappropriate for threshold tests and, if they were employed for this purpose, would indeed render this test clinically unusable.

Reneau JP & Hnatiow GZ. Evoked Response Audiometry. University Park Press, 1975. ISBN 0-8391-0752-8.

A thorough distillation of cortical ERA research papers up to the mid-1970s.

Other references

Cooper J & Lightfoot G. A modified pure tone audiometry technique for medico-legal assessment. 2000. Br J Audiol. 23: 37-45.

Downloadable files on Cortical ERA

The following files may be viewed or downloaded (from www.CorticalERA.com)

Please read the notes on this page relating to the file in question. Some of the files are quite large so unless you have a high speed internet connection be prepared to wait a while!

[Brochure](#) for the [ERA & OAE Course](#) (632KB) organised by the author in Harrogate, UK. The one-week residential course is held every May but usually sells out several months in advance. The brochure is in PDF format so you'll need to have Adobe Acrobat Reader. This can be downloaded free by visiting www.Adobe.com

NEW

Our current research interest - actually the introduction and methods sections of a draft paper we are preparing, is available [here](#). Please respect the Authors' copyright.

Run an "optimised" Cortical ERA test yourself! Scroll down for the latest videos.

The following video clips are examples of patients being tested using the author's system in Liverpool, UK. If you have a high speed (broadband) internet connection you will probably be able to view them on line (without having to download the files) and play them using Windows Media Player or similar software. Alternatively, right-click the link and download the file using "Save Target As". They are best viewed full screen. They are a little jerky since they were recorded at 8 or 10 frames per second.

The [first video](#) (5.79MB) is a 3 kHz bone conduction Cortical ERA test, with masking, lasting 4.37 minutes. Intensities used are 40, 20, 0 and 10 dBHL and yield a threshold of 5 dBHL. The lower panel is the incoming EEG (note how at the end of each sweep, the waveform becomes smoother - this is the 15 Hz low-pass digital filtering of individual sweeps). The upper panel is the averaging area. A repetition rate of 0.7Hz with 30% variability is used. Three sub-averages are acquired in a cyclical fashion and at the end of 15 sweeps a grand average (in red - this is a right ear test) is automatically created. Cursors are placed automatically, though the operator may reposition them, and a correlation coefficient calculated (lower left of the panel). At 40 & 20 dBHL only 15 sweeps are needed but at the lower intensities, closer to threshold, further averaging is undertaken. However, before this occurs, a 10 second stimulus-free period is provided to allow the response to recover and so minimise the effects of adaptation. An intensity series is displayed, allowing the operator to assess the responses and so establish the hearing threshold or the need for further testing.

The [second video](#) (15MB) is a 1 kHz air conduction simultaneous right & left Cortical ERA test lasting 7.37 minutes. The stimulus is presented in a random fashion to one or other ear (the colour of the incoming EEG waveform in the lower panel indicates **right** or **left** stimulation). The video begins just after the first intensity (60 dBHL) has been completed. Further averaging is undertaken at 40, 20, 0 and 10 dBHL. The results suggest thresholds of 15 dBHL in both ears.

NEW

The [third video](#) (6.4MB) is a segment of tests at 1kHz by air conduction using the simultaneous right & left Cortical ERA technique (3.22 minutes), this time shown on a

computer running Windows XP. Again, the video starts just after completion of testing at 60dBHL and demonstrates the acquisition of tests at 40 and 20dBHL. The quality of this patient's responses are less than ideal, but this example is included here to demonstrate that even so, the technique is viable. Clearly, in such cases the precision of the threshold estimate will be modest.

NEW

Now here's something you wouldn't be able to do using ABR.

The [forth video](#) clip (19.1MB) shows a 250Hz air conduction test on both ears (5.23 minutes). Right & left ear intensities of 50/50, 30/30 and 20/40dBHL are employed, and suggest CERA thresholds that were within 5dB of the patient's behavioural thresholds. Using ABR, issues of neural synchrony make responses to low frequency stimuli at low sensation levels almost impossible to record. In contrast, CERA responses at low frequencies are just as well defined, accurate and frequency specific as those at higher frequencies.

Take home message?

The author designed and developed this system for his own clinical and medico-legal use with hardware and software from [Cambridge Electronic Design](#) (the assistance of their software engineer Dr Geoff Horseman is gratefully acknowledged). Although this system is commercially available, it is a pity that such software has not been incorporated into existing ERA systems.

This is because there is no demand.

There is no demand because the possibilities and potential of this test have not been fully recognised.

That was a primary reason for the creation of this web site!

If you are impressed with this technique then please give the manufacturer of your ERA system a hard time - point them at this site and tell them to make one available!

Our Research

On this page we outline the CERA studies we are currently undertaking or planning.

Accuracy of the CERA threshold estimate in adults

Previous studies have used conventional stimulus presentation and data acquisition / manipulation methods. We know that our method is a good deal faster than conventional methods, mainly because we automate most of the predictable manual tasks. What we now need to demonstrate is the accuracy of the threshold estimate. Of course, this has been done before but not using our random pseudo-binaural stimulus and not at high frequencies. We are employing 24 volunteers (mostly hospital staff) whose pure tone audiogram (PTA) is recorded by experimenter 1. Their CERA is then conducted by experimenter 2, blind to the PTA results. Test frequencies of 1, 3 & 8 kHz (balanced order) have been chosen because most hearing disability schemes use the frequencies of 1, 2 & 3 kHz. Conventional wisdom suggests that the CERA amplitude is lower at high frequencies so we included 8 kHz to test this. Though not used in disability calculations, high frequencies are often helpful in matters of causation - demonstrating an audiometric notch associated with noise trauma.

Effectiveness of certain stimulus presentation features in increasing the N1-P2 amplitude

We developed our "Optimised" CERA test paradigm from the findings of the available literature (for details, see the page on this). However, we have taken much of this on trust and we certainly do not know whether there is any interaction between the effects of the parameters we have chosen. This study therefore addresses this issue by looking at them in isolation and in combination. Again, 24 volunteer staff are being used but only one ear is under scrutiny, at one frequency (3 kHz), at an intensity close to threshold (25 dB sensation level). In this study we hope to identify any effect on CERA amplitude of:

- varying the inter-stimulus interval of a monaurally presented stimulus
- inserting a 10s stimulus-free interval half-way through the averaging process to allow an adapted response to recover
- presenting the stimuli to one or other ear in a random fashion (at equal sensation level)

We also suspect that our random binaural stimulus yields responses from the two ears in a way that is not totally independent. To test for interaction, in addition to the above condition using equal sensation level, (25 dBSL) we have included tests in which the non-scrutinised ear is presented with stimuli at 40dBSL and at a sub-threshold level.

Further details of the above can be viewed as a downloadable PDF file from the downloads page.

The Author of www.CorticalERA.com

Guy Lightfoot (born 1953) has worked in adult diagnostic audiology since his appointment at the Royal Liverpool University Hospital in 1976 and now holds the appointment of Consultant Audiological Scientist and Head of the Clinical Measurement Section of the [Department of Clinical Engineering](#). Other appointments include

- Honorary Lecturer in Otorhinolaryngology, University of Liverpool
- Honorary Lecturer in Audiology, University of Manchester
- Immediate past Chief Examiner of the British Association of Audiological Scientists (now the BAA) CAC training scheme
- Continuing Professional Development Co-ordinator for the British Academy of Audiology.

Awarded the Thomas Simm Littler Prize by the [British Society of Audiology](#) in September 2004 for the most worthy contribution to audiology.



Education:

BSc (hons) in Physical Electronics, Newcastle, 1976

MSc in Audiology, Southampton, 1979

PhD in Click repetition rate effects on the ABR, Liverpool, 1991

Interests:

Training of Audiologists, ERA, vestibular assessment, instrumentation.

Courses:

Organiser & Lecturer, the annual 1-week ERA & OAE Course (Harrogate, UK);

Organiser & Lecturer, course on Electrophysiological Assessment following Newborn Hearing Screening for the UK's NHS Programme.

Email address for feedback on this site: G.Lightfoot@Liverpool.ac.uk

Glossary

Amplitude (of a response): The potential difference (voltage) between two points on a waveform, typically a peak and trough, used to quantify the magnitude of the response.

Auditory Brainstem Response (ABR or BSER): The family of peaks (& troughs) recorded in the 10ms following a brief stimulus such as an acoustic click. On a simplistic basis, each peak has an anatomically distinct generator so the amplitude and latency intervals of the peaks may be used to make gross inferences on the status of the generators or their interconnections. Ironically, peaks I & II arise from (the distal and proximal portions of) the auditory nerve rather than from within the brainstem itself. The generator of peak III is thought to be the cochlear nucleus, peak IV the superior olive, peak V the lateral lemniscus though this model is an over-simplification for the later peaks, especially peaks V, VI & VII, in which multiple generators are implicated. Wave V is often employed in the assessment of hearing since it can be recorded close to the audiological threshold.

Auditory Neuropathy: An abnormality of the auditory neural pathways not evident from imaging studies leading to absent or abnormal ABR and/or later responses rather than from a defect within the organ of corti.

Averaging: A standard means of improving the signal to noise ratio (and therefore our ability to record an identifiable response) based on the assumption that the signal (response) occurs at a fixed time (latency) after the evoking stimulus whereas the noise is random. Multiple (n) samples of activity are recorded over a fixed time period following each stimulus and are summed. The signal will sum algebraically whereas the noise, if truly random, will sum by $n/\sqrt{2}$.

Contingent Negative Variation (CNV): An "expectation" response usually evoked by a stimulus that the subject associates with a second subsequent stimulus, often of a different modality. For example paired stimuli may be an auditory tone followed by a visual flash. If the subject has been repeatedly exposed to many pairs of these stimuli, not only does the tone evoke its own auditory response, a distinct response occurs in readiness for the flash, even if it is not given.

Electrocochleography (ECochG): The recording of electrical events arising from within the cochlea. These include the (neurogenic) compound action potential (synonymous with peak I of the ABR), the cochlear microphonic and the summing potential, from which information regarding the function of the cochlea may be gleaned. A principal clinical application is in the diagnosis of Ménière's Disease. The small size of the ECochG when recorded using scalp electrodes requires that a special electrode is used allowing placement closer to the cochlea. Originally, trans-tympanic needle electrodes were used but this invasive technique has been largely replaced with an electrode in contact with the tympanic membrane or ear canal wall.

Epoch (time base or window): The period over which the response is recorded - the horizontal axis of an evoked response waveform. This most often starts at the instant of stimulus onset and extends to beyond the latest possible region of interest of the response. The epoch may start before stimulus onset to provide the user with a sample of non-response "baseline" activity or it may start after the stimulus to avoid recording an unwanted artefact associated with the stimulus.

Filters: The analogue or digital means of removal of unwanted noise from the data, based on its frequency content. Frequency regions beyond the spectral content of the response are attenuated whilst the frequency band of interest is not. The upper and lower boundaries of the "pass band" are usually separate high-pass (rejecting low frequencies) and low pass (rejecting high frequencies) filters.

Frequency Specificity: The extent to which a stimulus, or the response it evokes, relates to a specific or narrow region of audiometric frequencies. This is related to the effective duration of the stimulus and to the way in which it starts and stops. Unfortunately, the audiologically ideal tones used in pure tone audiometry do not evoke many of the responses used in ERA (which are onset responses) so the stimulus needs to start and stop fairly abruptly. However, this leads to a spread of energy to frequencies other than the fundamental of the stimulus (spectral splatter). Since there is a link between response latency and the maximum rise time of the stimulus, early responses such as the ABR require very brief stimuli that are inherently less frequency specific than that available for use with the late responses, such as N1-P2.

Input-Output Function: This is the relationship, expressed as a graph, between an aspect of the stimulus (e.g. intensity) and an aspect of the response (e.g. latency). Knowledge of normal and common pathological I/O functions is helpful in response interpretation (e.g. estimating threshold). Measuring an individual's I/O function can also be helpful (e.g. as an indicator of recruitment).

International ERA Study Group: The IERASG was formed in 1970 and comprises researchers, scientists, audiologists and clinicians with a common interest in ERA & OAE techniques. The group holds a 4-day symposium every two years. Go to Links to visit the IERASG web site.

Inter-Stimulus Interval (ISI): The time from the start of one stimulus to the start of the next, the reciprocal of stimulus repetition rate. Confusingly, ISI is not the duration of the silent interval between stimuli (except for stimuli of zero duration!).

Latency: The time from the instant of stimulus onset to a specific feature or peak in the response.

Masking: The process (or the sound used in the process) of temporary elevation of the hearing threshold, most often applied to the better hearing ear to inhibit the detection of sounds presented to the worse ear. Masking noise may be unfiltered (wide band or white noise) or filtered in some way (e.g. narrow band, centred around the frequency of the test tone). In some ERA tests noise is presented, together with the stimulus, to the test ear in order to improve the frequency specificity of the response or to limit the effective spectrum of the stimulus.

Middle Latency Response (MLR): As the term suggests, responses falling under this heading occur after the early latency responses of the ABR and before the long latency cortical responses, roughly in the range 15 - 70 ms. Peaks carry the labels Na, Pa, Nb, Pb etc. It is debatable whether P1 (at around 50ms) is the last of the middle latency responses or the first of the long latency responses. There is some debate over the generators of MLR but most agree that the medial geniculate nucleus and auditory cortex are implicated.

Mis-Match Negativity (MMN): If about 10% of stimuli presented to the subject is different in some way to the majority of the stimuli, in addition to the response elicited by the stimulus (e.g. N1), there is an extra negative wave (or an enhanced N1) in the range 100-300ms that is not otherwise present. The MMN may be isolated by subtracting the waveforms evoked by the "rare" and "frequent" stimuli. The MMN does not rely on the subject's attention to the "rare" stimulus, nor on different neural pathways - it can be evoked by a stimulus that is simply shorter than the "frequent". MMN is thought to be generated by the auditory cortex and frontal cortex.

P300: The stimulus paradigm of the P300 is similar to that of the MMN (see above), using an "oddball" stimulus. Unlike the MMN, if the subject is asked to attend to the "rare" stimuli or perform some task in response, an additional positive wave occurs at about 300ms. The generators of P300 are not well understood.

Plateau: The duration (normally specified in milliseconds or optionally by the number of cycles of the tone) of that part of a stimulus tone envelope that has a constant amplitude. See also notes under Tone Burst.

Repetition Rate: The rate at which stimuli are repeated during the averaging process. It is the reciprocal of inter-stimulus interval.

Rise Time: The duration (normally specified in milliseconds or optionally by the number of cycles of the tone) of that part of a stimulus tone envelope whose amplitude rises from zero to the full value. In cortical ERA the rise usually has a linear slope though a more complex transition may be used to maximise the frequency specificity of the stimulus. Traditionally, the fall time is the same as the rise time.

Sweeps: The number of times a stimulus is repeated and ensuing response is summed for the averaging process.

Temporal Integration: The process by which the loudness of a sound is reduced because of its short duration. The effect occurs only for stimulus durations less than about 100ms: the shorter the stimulus, the quieter it becomes (and the more elevated the threshold becomes) because the ear integrates the energy of the stimulus over time.

Threshold: The lowest intensity stimulus that can be detected. In most psychometric test the threshold corresponds to a 50% chance of detection. In clinical auditory evoked potentials the constraints of test time usually limit the intensities used to 10dB steps. The threshold may be taken as the minimum intensity at which a repeatable response is identified or some form of interpolation rule may be used. For example the threshold may be taken as the intensity midway between response and non-response levels, providing that the response meets certain criteria such as minimum amplitude or maximum latency.

Tone Burst: The stimulus of choice for Cortical ERA tests. It comprises a pure tone of the desired audiometric frequency that has a defined start (rise time), duration (plateau) and end (fall time). There is no official distinction between a tone burst and a tone pip but in practice, the term tone burst is often used when the stimulus has an overall length of more than about 20ms (and the plateau is longer than the rise/fall time), whereas a tone pip length is less than 20ms (and usually has a plateau which is the same or shorter than the rise/fall time). The International standard specifying these stimuli, IEC 645-3, confuses matters somewhat by introducing a new term: brief tones. Further, the term duration is defined as the plateau plus half the rise time plus half the fall time. There are several other concerns over the content of IEC 645-3, which is currently under review.

Vertex: The site of the active electrode when recording Cortical ERA. Also known as Cz under the International 10-20 electrode system, it is on the midline, and equidistant from the nasion (bridge of the nose) and the inion (ridge at the back of the head). For the purposes of threshold estimation, the site of the vertex electrode need not

be precise since the topography of the response is gradual. Asking the patient to put their finger on the top of their head (not their crown) usually locates the vertex to within a centimetre or so. However, the use of a high forehead site leads to the unnecessary loss of response amplitude and is not appropriate.

Oto-Acoustic Emissions: First identified by David Kemp (Professor of Auditory Biophysics at University College, London) in the late 1970s, OAEs are sounds generated from within the cochlea (outer hair cells) and recorded from the ear canal. OAEs may be spontaneous or evoked by sounds, and are generally absent in cases of significant cochlear dysfunction. As such, OAEs have become popular as an efficient means of screening for hearing loss in neonates and in the investigation of cochlear function. Professor Kemp is a member of the faculty of the ERA & OAE Course.