



Recommended Procedure

Auditory Brainstem Response (ABR) testing for Post-newborn and Adult

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General foreword

This Recommended Procedure represents a brief synthesis of the current evidence-base and consensus on Auditory Brainstem Response testing post-newborn and adults, as prepared and reviewed by national and international experts, and approved by the British Society of Audiology (BSA).

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2. Introduction

2.1 Abbreviations

ABR	Auditory Brainstem Response
AC	Air-Conduction
AEP	Auditory evoked potentials
ANSD	Auditory neuropathy spectrum disorder
AR	Artefact rejection
ASSR	Auditory Steady-State Responses
BC	Bone-Conduction
BSA	British Society of Audiology
CAEP	Cortical Auditory Evoked Potentials
cCMV	Congenital cytomegalovirus
CCTV	Closed circuit television
ckABR	Click evoked Auditory Brainstem Response
CM	Cochlear microphonic
CR	Clear Response
dBeHL	Estimated PTA from electrophysiological thresholds

dBnHL	Stimulus level relative to adult psycho acoustic threshold. In these guidelines the NHSP reference equivalent threshold levels are used
EEG	Electroencephalogram
EP SIG	Electrophysiology Special Interest Group
Inc	Inconclusive
nABR	Neurological Auditory Brainstem Response
NDCS	National Deaf Children's Society
OAE	Otoacoustic emission
PTA	Pure-Tone Audiometry / Audiogram
RA	Response Absent
SNR	Signal to noise Ratio
tpABR	Tone pip Auditory Brainstem Response
VRA	Visual Reinforcement Audiometry

2.2 Scope

The scope of this document covers testing infants, children and adults using Auditory Brainstem Response (ABR), an electrophysiological technique. This document assumes the testing is primarily performed when the patient is in natural sleep. Where sedation or anaesthesia is necessary or when testing is performed when the patient is awake, this will be stated. It will also cover the use of the Neurological ABR (nABR).

For pragmatic reasons, this document will use the following arbitrary terms: baby (corrected age less than or equal to 12 weeks (84 days) which are excluded from this guidance, infant equal to or greater than 12 weeks and less than 24 months, child equal



to or greater than 2 years and less than 16 years, adult equal to or greater than 16 years.

Note that any baby under three months should be managed with reference to the BSA Practice Guidance for the early audiological assessment and management of babies referred from the Newborn Hearing Screening Programme version 3.1. (BSA 2014c) and the related ABR guidance (BSA 2019a)

Behavioural testing should ideally be used to establish threshold measurements for air-conduction (AC) and bone-conduction (BC) using age appropriate methods such as visual reinforcement audiometry (VRA), or pure-tone audiometry (PTA), as appropriate. These measurements should be carried out according to BSA guidance. Where this is not possible due to developmental issues, cognitive/motor issues or non-organic behaviour an electrophysiological assessment should be considered to objectively establish audiological thresholds.

This document is only concerned with ABR and therefore excludes other auditory evoked potentials (such as cortical auditory evoked potentials (CAEP) or auditory steady-state responses (ASSR)). Specific BSA guidance on these techniques should be consulted.

3. General Requirements

3.1 Equipment

Calibration must be sufficiently comprehensive to allow threshold measurement using clicks by both air-conduction (AC) and bone-conduction (BC), tone pips (also known as brief tones or short tone bursts), and/or chirps. Equipment must be calibrated annually to the reference levels given on the BSA website (NHSP Calibration Data 2012 <https://www.thebsa.org.uk/wp-content/uploads/2019/04/NHSP-Calibration-Data-2012.pdf>) and undergo regular safety and electrical testing in accordance with BS EN IEC 60601 and local protocols. Stage A listening checks must be carried out before each session and recorded in line with local procedure.

3.2 Staff training and expertise

Within each test session as a minimum, the lead person should have the relevant training and expertise to perform the testing, interpret the waveforms and discuss the results with patients and carers.

The expertise should include the ability to make appropriate and clinically efficient decisions for test strategy, accurately interpret ABR waveforms, accurately determine thresholds (including when and how to use masking) and to know how to deal with unusual or unexpected waveforms or results. In addition, staff within the team should have expertise in the discussion of results with parents and patients and the possible options in management, thus it is recommended that staff attend an appropriate course such as 'sharing the news'.

As good practice it is recommended that the department takes part and engages with external peer review (guidance for which is currently in preparation from the BSA). Paediatric services should be aware of and work within the NHS relevant standards. To build skills it is recommended that a process for auditing of results is in place.

3.3 Test Environment

It is preferable to have an acoustically quiet environment in order to assess hearing threshold. This is usually achieved by a suitable sound-treated or sound-proofed room. However where this is not possible then it should be noted that tests performed in areas where the ambient noise is above that normally used in audiometry it may not be possible to detect milder hearing losses.

Regardless of the age of the patient, the test environment needs to be suitable for electrophysiological testing, with minimal electrical interference. A quick guide to sources of interference and suggestions can be found in section 8.1 Appendix A.

3.4 Appointments

The appointment should ideally be confirmed in writing by the Audiology service along with clear written information about the appointment including the tests that are planned, and their likely duration.

3.4.1 Infants/Children

In paediatric settings it is desirable to have a family and child friendly waiting room with space to feed, change and settle children. Also a travel cot or child friendly bed in the testing room may be appropriate.

For infants and children where testing in natural sleep is envisaged, the information given prior to the appointment shall state that the child needs to arrive awake but tired, and ready to sleep in clinic. Appointment times should be flexible within reason to fit in with the child's routine. Time should be allowed within the appointment for the child to be settled and ideally there should be facilities for preparing feeds/ feeding etc.

It should be clear that this is an assessment appointment and that parents are welcome to be accompanied by a friend or relative, if they wish. Any practical upper limit on the number of adults wishing to attend should be stated in the appointment letter. Where practically possible, parents should remain throughout the entire procedure and be involved in the preparation of the child as their presence and involvement may greatly reduce the distress to the child caused by separation anxiety and often results in improved behaviour of the child. Reference should be made to the National Service Framework for Children (Department of Health 2004).

3.4.2 Adults

For adults, a reclining chair or couch in the testing room is beneficial to allow them to relax. Electrophysiological testing of adults should be in conjunction with a battery of other testing such as PTA. In suspected possible non-organic patients it is worth informing the patient that the results will be compared to the PTA. If tABR is going to be attempted in an awake subject, extreme caution should be taken interpreting and reporting the results and it may therefore be beneficial to consider other forms of electrophysiological testing e.g. CAEP, for which there is a separate BSA Recommended Procedure (BSA 2016). When the test is carried out from a separate room it is essential to be able to monitor the patient and communicate with them through an intercom system and window/CCTV system.

No more than two patients should be booked into a morning or afternoon clinical session to allow sufficient time for each patient. In a theatre setting it may not be possible to book more than one patient. It is important to liaise with theatre staff when planning sessions to ensure sufficient time is reserved for each case.



3.5 Communication with patient, parents and/or carer

The reason and procedure for each test should be explained to the patient and/or the parents / carers. At the end of the assessment, the patient and/or parents / carers should be provided with appropriate verbal and written information. This may include a checklist or departmental leaflet, where hearing is satisfactory. Where a hearing loss is confirmed the appropriate support should be given in accordance with local and national guidance. If the type of hearing loss is yet to be determined, then contact details (telephone/ departmental email address) should be given together with the details of the next appointment.

3.6 Electrodes

The skin should be prepared using an appropriate paste and/or gauze and single use electrodes should be used. For a Cz (vertex) placement the electrodes with integral adhesive can be difficult to attach securely due to the patient's hair. Disposable EEG-type electrodes with electrode paste, secured by tape, are recommended. All procedures must comply with local infection control policies. It is essential to ensure that inter-electrode impedances are below $5k\Omega$, preferably below $2k\Omega$ and are balanced as far as practicable across pairs of electrodes. This will be especially important in an operating theatre setting, where electrical interference is likely to limit the quality and precision of the results.

If a single-channel recording is to be used, the following electrode placement is recommended:

Infants:

Positive (non-inverting) electrode: high forehead (avoiding the anterior fontanelle)

Negative (inverting) electrode: ipsilateral mastoid

Common electrode: contralateral mastoid

Children/Adults:

Positive (non-inverting) electrode: Cz (vertex)

Negative (inverting) electrode: ipsilateral mastoid

Common electrode: contralateral mastoid

Either configuration should result in Wave V being plotted upwards.

Different equipment may recommend a range of electrode montages and therefore the tester should ensure they know the rationale for the manufacture's suggested montage and be able to justify their choice of montage.

Alternatively a 4 electrode array could be used if additional testing is being considered, for example 2-channel ABR or ASSR.

4. Sequence of Tests

4.1 Introduction

The order and range of tests undertaken will be greatly influenced by the sleep state of the patient and the diagnostic purpose of the test. Sleep or a very relaxed awake state (with little muscle activity) is highly desirable for ABR testing but is often difficult to achieve in children without a form of sedation.

For the initial diagnostic appointment, where no previous results have been obtained it is recommended that the initial stimulus is 4 kHz tpABR at 40-50 dBnHL. Where behavioural or previous results indicate a significant hearing loss, a louder starting level may be more appropriate.

Discharge criteria should be defined locally as it will be determined by the clinical picture. A suggested minimum discharge criterion could be the establishment of air-conduction 4 kHz tone pip auditory brainstem responses (tpABR) thresholds predicting estimated hearing thresholds of ≤ 30 dBnHL in both ears. There are some conditions, such as a permanent unilateral hearing loss, cCMV, meningitis and septicaemia where ideally thresholds should be obtained down to 20 dBnHL, however this will vary depending on the clinical question being addressed and the test environment.

No other testing will usually be required if hearing is normal at 4 kHz, except in cases of permanent unilateral hearing loss, cCMV, meningitis and septicaemia or where more information is needed clinically, when 1 kHz testing is also recommended. The main reason for starting with 4 kHz, is that the quietest parts of speech are around this frequency and using a lower frequency may miss some ski slope hearing impairments. It also has a practical advantage as 4 kHz is the frequency that testers are more familiar with using and therefore could be thought of as being the easiest of the tpABR to interpret.

After assessing 4 kHz in both ears, if the threshold is significantly raised then it is important to test at lower frequencies, for example 1 kHz.

4.2 Test Strategy

In general, the testers should use the BSA ABR testing in Babies (2019a) guidance on ABR testing in babies as a reference but when performing ABR tests on infants, children or adults, there can be a variety of technical challenges, most of which are related to interference from the patient or from other equipment.

It is essential that the clinician maximises the information obtained to answer the clinical question being addressed by the ABR assessment. In many clinical scenarios the following strategy is appropriate and may be followed and solutions attempted, in the following order, until satisfactory results are obtained.

Using the test parameters outlined in appendix B, start by testing 4 kHz tpABR using AC in the ear with the suspected better hearing. See below for steps to be taken when an artefact rejection (AR) of 5µV leads to total rejection. All the AC and BC correction factors that are stated in NHSP guidance still apply and a summary of this can be found in Appendix C. Appendix D sets out the definition of ABR thresholds.

Following establishing the AC threshold in one ear at 4kHz, the tester can move to test the other ear by AC at 4 kHz. If the AC threshold is raised, test using BC at 4 kHz tpABR to determine if any raised threshold is due to a conductive component, though at this stage there may be insufficient information available to select an appropriate level of noise for masking the non-test ear.

Note that the 2-channel method of determining whether cross-hearing is present, whilst valid in the newborn period, should not be used for adults or children over 2 years because it may give unreliable results.

This may be all that is possible to obtain on a good test session with infants and children but where possible, testing should continue until all the required information has been obtained.

Where possible, an AR of 5µV should be used. This low AR allows a modest number of sweeps (e.g. 2000) to be used to usually produce good results although the requirement for an SNR of 3:1 must always be the overriding goal.

If the majority of sweeps are rejected, then the tester should attempt to identify and exclude the source of the interference. Ensuring that the electrode impedances are <5

k Ω and balanced, should minimise electrical interference. If the noise is electrical and cannot be eliminated completely, then consider applying the 50 Hz notch noise filter¹. Where the interference is patient-generated or is electrical but not of mains (50 Hz) origin then the cut-off frequency of the high-pass filter may be raised from 30 Hz to 50 Hz. Further increasing the cut-off high-pass filter greater than 50 Hz is not recommended as this will attenuate not only the interference but also substantially attenuate the response.

If this is unsuccessful the next step to consider is to increase the AR level. Figure 1 (from Lightfoot & Stevens 2014) summarises the need to increase the number of sweeps as the AR level is increased in order to maintain a sufficient SNR. If the waveforms are noisy due to electrical interference in theatre (see 5.6) or an unsettled patient, then ensure that more sweeps are carried out either per run, or distributed over multiple runs average them in a pair-wise fashion, as this will help reduce noise. For example when performing 4 averaging runs it is suggested that runs 1 and 3 are averaged and runs 2 and 4 are averaged (use a weighted add option). Start by increasing the AR level to 7 μ V and increasing the number sweeps as in Figure 1.

In adverse recording environments, the AR level may need to be increased to over 10 μ V in order to collect sweeps. This is acceptable only if the tester understands that in order to achieve an acceptable SNR in the recording, doubling the AR level requires 4 times the number of sweeps and even more sweeps could be needed when the AR is >10 μ V. Failure to use an adequate number of sweeps is likely to result in inconclusive waveforms.

The recommended gain is 240 000 and gain is also related to AR. The tester should have knowledge of the trade –off if they are to change the gain. The analogue to digital converter (ADC) of most systems permits a maximum output voltage of 5V (5,000,000 μ V). The signal from the patient (which is mostly unavoidable noise) is nowhere as big as this, so the signal needs to be amplified. For example, amplifying a signal of $\pm 10\mu$ V by a factor of 240,000 (a gain of 240,000) will result in a signal of 4.8V, thus taking advantage of almost the entire available dynamic range of the ADC. If the AR is to be increased above $\pm 10\mu$ V the amplifier gain must be correspondingly reduced, for example to 150,000, where an AR up to $\pm 16\mu$ V is possible.

[1] When a notch filter is used this must be noted in the clinical report. The available evidence is that notch filtering does not distort the newborn ABR, with the exception of testing at 500 Hz where waveform distortion has been observed and could compromise waveform interpretation. At 500 Hz therefore the notch filter must not be used. (Updates to NHSP guidance for post-screening diagnostic testing, Update 1: August 2015).



If the equipment has Bayesian averaging then this should be employed.

AC click ABR (ckABR) should be considered for threshold estimation purposes only if it is clear that it may not be possible to measure AC tpABR thresholds, where it is important to quickly get some estimate of hearing threshold or where there is no tpABR response at the normal maximum stimulus level. In the latter case, it may be considered clinically useful to see if an ABR response to click stimuli can be recorded (the ckABR response may be recordable at high stimulus levels with absent tpABR). Such additional assessment is important when the testing conditions are not ideal (e.g. in operating-theatre setting) and behavioural testing is unobtainable and the main aim of the procedure is to get an approximate baseline for the hearing thresholds.

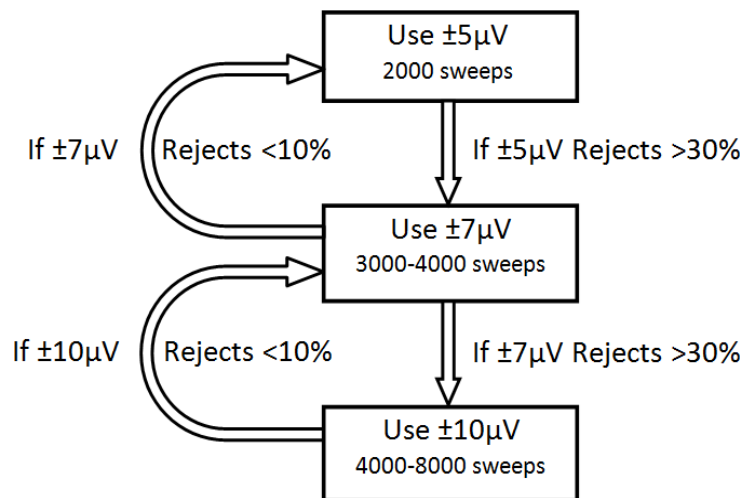


Figure 1: Flow diagram illustrating a possible clinical decision making process for determining the optimum artefact rejection level to use and the number of sweeps needed.

4.3 Changes in ABR stimulus level and testing at higher levels

Changes in stimulus level should normally be in 10 dB steps depending on the nature of the case. Occasionally, e.g. where there is strong recruitment, a 5 dB step may be useful, but care should be taken not to spend time on small changes in stimulus levels at the expense of producing definitive outcomes at 10 dB intervals around threshold. There may also be occasions when it is better to use larger steps, for example where an infant may stay asleep for only a few test levels. As an illustration of this, by testing at 40, 60

and 80 dBnHL and determining that the ABR threshold lies between 60 and 80 dBnHL, a more useful outcome is achieved than by having increased the level in 10 dB steps from 40 dBnHL and being able to determine only that the ABR threshold is above 60 dBnHL.

If there is no response at the normal maximum permissible stimulus level to tpABR (as defined in BSA NHSP Early Assessment Guideline (2014²) or only abnormal waveforms at high stimulus levels (≥ 75 dBnHL), then Auditory Neuropathy Spectrum Disorder (ANSD) may be present. Tests should then be carried out for cochlear function. Refer to the BSA guidelines on Cochlear Microphonic (CM) (BSA 2019b) or testing and guidelines for the assessment and management of ANSD in young infants (BSA 2019c) which should be followed.

4.4 Awake patient

It is always preferable to test the patient using ABR whilst asleep. However this is sometimes not possible.

tpABR or ckABR testing can be attempted with a patient who is awake, but only if they are physically very relaxed, with a quiet background EEG³. Extra care must be taken to ensure that any results collected are of good quality (residual noise below 40 nV) and replicated. One of the most important issues will be to know when to stop averaging at a given stimulus level. It is better to collect a few results of high quality that can add value to the clinical test battery than report on inconclusive or inaccurate results that are degraded by noise. If accurate results are needed and the patient does not sleep or settle then sedation should be considered in collaboration with medical staff and in line with local hospital procedures for administration and after care. If the patient is awake and the background “EEG” is too noisy, ABR testing is unlikely to yield reliable results. In such circumstances it is appropriate to reconsider other forms of audiology testing. With an adult patient, CAEP or 40 Hz ASSR testing should be considered as viable alternatives.

² For adults and children over 2 years the maximum stimulus levels for both inserts and supra-aural earphones are those quoted for supra-aural earphones in the Early Assessment guidance since there is no age-related correction for age for these groups.

³ “EEG” in this context means the incoming electrical activity sensed by the electrodes from brain. In practice what we see is usually dominated by muscle activity, cardiac activity and electrical interference rather than true EEG activity.

4.5 Sedation and theatre

Sedation is not usually necessary in babies and should be used in infants only with full consultation with a wider medical team. One of the advantages of early assessment is that babies/infants can be tested relatively easily during natural sleep. Parents need to be made aware of the requirements for a sleeping or settled infant and where possible appointments should be timed appropriately.

Where sedation or general anaesthesia is being considered, the patient should be under the care of an appropriate physician. Each centre must adhere to their hospital requirements and gain consent from patients as required according to each hospital's policy and make necessary arrangements for admission onto an appropriate ward if necessary. The patient and/or carer should give their consent for the audiology assessment. The patient will need to be given separate information about the admission times on the ward, nil by mouth procedure, etc. The clinician should aim to coordinate the appointment with any other treatment the patient may be receiving, as it is often favourable to have everything carried out at the same time.

The operating theatre is not an ideal environment for ABR measurements, but if care is taken, good results can usually be obtained. It is essential that the patient is kept anaesthetised for the duration of the test and this will require communication between the audiologist and the anaesthetist, in particular with regard to the anticipated duration of the procedure. Some equipment commonly used in theatre (warming blankets, pulse oximeters) may create additional interference and if this is the case should be avoided, following consultation with the anaesthetist. The ABR equipment should be plugged directly into a mains socket and not an extension. If a mains extension is unavoidable, no additional equipment shall be connected to the extension. The grouping (braiding or twisting together) of electrode leads and their physical separation from other cables is particularly important in theatre as a means of minimising electrical interference. Headphone covers should be used with supra-aural earphones after any surgical ear procedure. There are some advantages to using inserts, firstly if the ear has been aspirated or cleared of wax and there is still some fluid then elevating the tubing could reduce infection control risks and the tubing is easier to change. Secondly inserts can help reduce the level of ambient noise if the ear tip has been fitted well.

However, due to the smaller ear canal volume in infants and children, inserts can deliver a higher sound level than in adults, as discussed in The BSA Practice Guidance for the early audiological assessment and management of babies referred from the Newborn Hearing Screening Programme (BSA (NHSP), 2014), resulting in a wider margin for error and the need to set lower maximum stimulation levels.

Clinicians should be aware that following middle ear surgery there may be a temporary threshold shift or a conductive loss associated with a blood-filled ear canal. It is also possible to see a conductive loss reappear during testing if unaspirated fluid refills the middle ear cavity.

4.6 Definition of accepting responses

ABR threshold is defined as the lowest level at which a clear response (CR) is present, with a response absent (RA) recording at a level 5 or 10dB below the threshold, obtained under good recording conditions.

For CR there must be a high degree of correlation between the replications and the waveforms should show the expected characteristics in terms of amplitude, latency and morphology. The size/amplitude of the response (as judged from the wave III/V to the following SN10 trough) should be a minimum of 40 nV and at least 3 times the background noise level (the noise level can be estimated from the average difference between optimally superimposed waveforms). The waveform should be judged over the whole time window excluding any stimulus artefact.

Waveforms should be compared with those at other stimulus levels (where available) to confirm that they follow the expected changes with stimulus level.

The SNR could be relaxed to 2.5 to 1 in difficult testing conditions such as in the operating theatre but in so doing, the tester must acknowledge the increased risk in mistaking noise for a valid response and thus underestimating the ABR threshold.

For RA the waveforms must be appropriately flat, with no evidence of a response and the average difference (noise) between a pair of optimally superimposed waveforms should be less than or equal to 25 nV (using the same method for measuring background noise for CR described above). All other responses not meeting either criteria should be marked Inconclusive (Inc). The residual noise criterion could be relaxed (but to no more than 40 nV) in difficult testing conditions such as in the operating theatre but in so doing, the tester must acknowledge the increased risk in failing to identify a small response obscured by noise and thus overestimating the ABR threshold.

5. ABR in assessment for candidacy for cochlear implantation

ABR testing can be performed as part of the audiological assessment of candidacy for CI in infants, children and adults.



Frequency specific results are required for CI. NICE Guidelines (NICE 2019) state that a minimum of two frequencies across 500 Hz, 1, 2, 3 and 4 kHz should be tested and interpreted along with other audiological testing (e.g. otoacoustic emissions (OAEs), tympanometry and behavioural hearing tests).

In patients where ABR results are absent or of abnormal waveform morphology, the possible presence of ANSD must be considered and the appropriate investigations employed (see BSA 2019b and 2019c).

As improvements in ABR and in behavioural thresholds over the early months of life have been reported in some infants, a further repeat ABR at a later age may be helpful in order to confirm the diagnosis. If this is felt to be helpful for the management of the individual case, then a re-test at around 12-18 months of age should be considered as per the BSA guidance.

6. Reporting

At each test session results should be documented in detail as the session proceeds. It is important that appropriate professionals are kept informed of the outcome of each episode of the assessment (even if few or no results are obtained). Non-attendance and the subsequent plans should be reported appropriately.

The report should include:

- A summary of the reason for the test session.
- A brief medical history of relevant factors relating to hearing loss.
- A summary of the electrophysiological results, including warnings where the threshold has not been accurately determined, where threshold is above the maximum available stimulus level or where the results are subject to poor recording conditions. The consistent use of \leq , $=$ & $>$ when reporting results is preferable to phrases such as “responses seen down to...”
- A description of testing conditions such as sedation or anaesthetic used.
- A description of the test environment including information regarding any factors which may have influenced test interpretation.
- A full outline of any adjustments to parameters required and information written for a lay reader on the impact these may have on result interpretation.

- A note of any other factors that might affect the estimate of the hearing threshold, as measured by the ABR (e.g. possible ANSD, evidence from other tests of possible neurological damage to the brain).
- A report of any consistent behavioural reactions taking account of their limitations.
- A comment on any other test results obtained at the same session.

7. The Neurological ABR

7.1 Introduction

The main body of this document describes the *threshold* application of the auditory brainstem response (ABR) to provide an objective estimate of the auditory threshold, which can be thought of as a surrogate for the pure-tone audiogram (PTA). This appendix describes the use of the ABR to assess and evaluate the functional integrity of the ascending auditory neural pathways. The *neurological* ABR (nABR) is therefore less concerned with the status of the ear but can instead be considered a neurological test.

In the threshold ABR, the main test objective is to determine whether a response to a particular audiological stimulus is present (inferring that the stimulus has been detected by the ear and is therefore above the hearing threshold) or absent (stimulus not detected by the ear and therefore below the hearing threshold) and the test parameters, procedure and waveform interpretation techniques are optimised to that end. Briefly, an ABR waveform is recorded at a variety of stimulus levels until the ABR threshold becomes apparent. In the nABR, the test focuses not on response *detection* but rather on *analysis* of the nABR waveform as a measure of neurological function. It is therefore unsurprising that the two ABR tests differ in terms of test parameters, procedure and analysis.

In the nABR, a high-level click stimulus, often at a single stimulus level (such as 80 dBnHL) is employed to evoke a large action potential in the auditory nerve (ABR wave I). The latency and amplitude of the ensuing ABR waves and the inter-peak latencies can provide evidence of the function or dysfunction of the ascending neural pathway. A wide variety of pathologies may influence the recorded nABR, including space-occupying tumours (e.g. vestibular schwannoma), hydrocephalus, and diffuse or systemic disorders that affect neural synchrony such as multiple sclerosis and ANSD. Analysis of the nABR waveform can sometimes provide useful information about the approximate location or severity of a disorder.

When using the threshold ABR to assess peripheral hearing sensitivity we would like to be able to assume that any abnormal response is the result of a raised hearing threshold

rather than any neurological abnormality. Conversely in the nABR we would like to assume that any abnormal response is the result of a neurological rather than any audiological problem. In reality we can make no such assumptions and must be careful to examine the case history for valuable clues and exploit other, independent, indicators of audiological and neurological status. Knowledge of the ways in which a hearing loss can influence the ABR is important when considering nABR test strategy and waveform interpretation, as is our willingness to perform separate threshold ABR and nABR tests to aid diagnosis when necessary.

7.2 ABR generators and the normal ABR response

The ascending auditory pathway comprises fast and slow fibres so the mapping of ABR peaks (or waves) to anatomical generators becomes increasingly confounded as we progress up the pathway. That said, the main contributors of the following ABR waves are generally thought to be:

Wave I: distal portion of the auditory nerve

Wave II: proximal portion of the auditory nerve

Wave III: cochlea nucleus

Wave IV: superior olivary complex

Wave V: lateral lemniscus

Wave VI: inferior colliculus

This is a very simplistic view and uses the popular peak labelling convention first suggested by Jewett and Williston (1971). The generators of waves I to III are on the side ipsilateral to the side of stimulation whereas 90% of ascending fibres beyond the cochlea nucleus cross to the opposite side of the brainstem (Møller et al. 1995; Burkard & Don 2012).



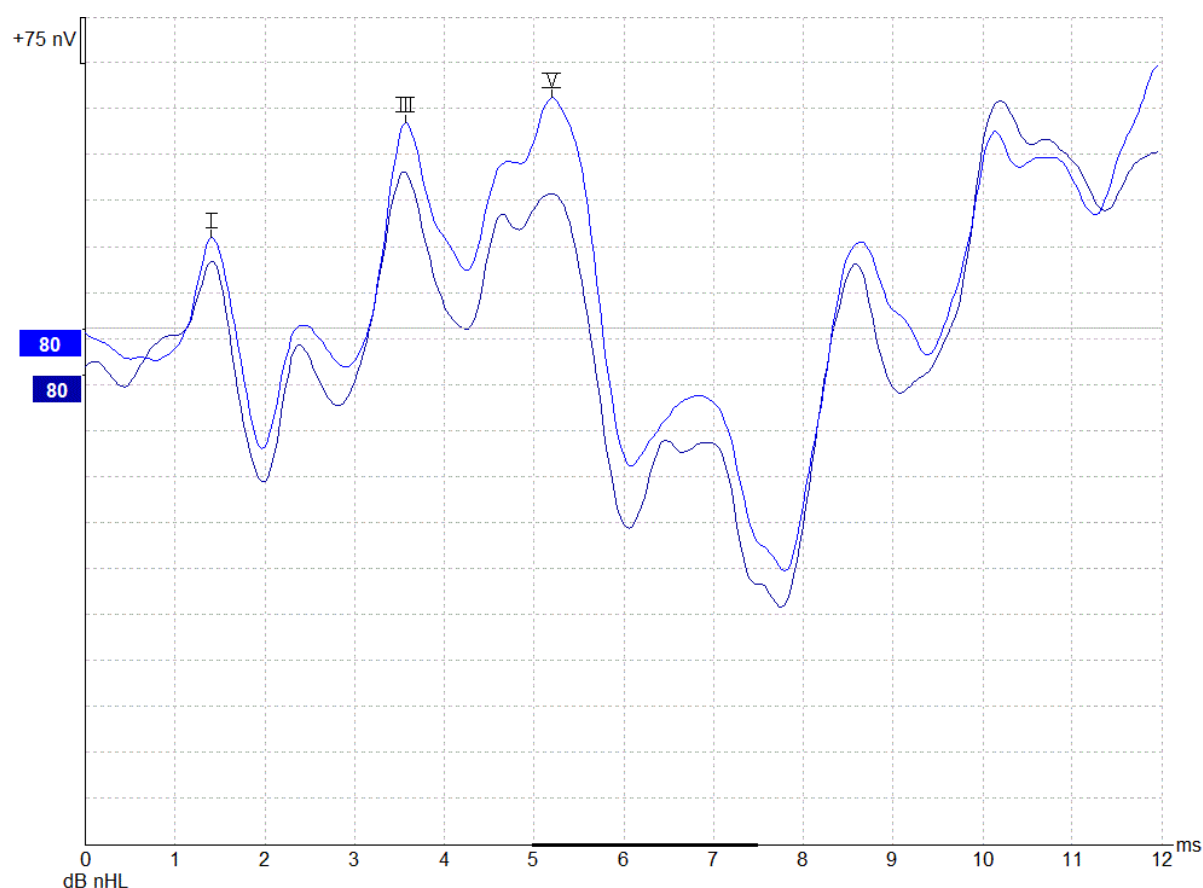


Figure 2 A normal adult nABR. Waves I, III & V have been labelled; waves II, IV & VI are not always marked because they are less reliably identifiable than I, III & V.

7.3 Factors affecting the ABR

In the normal adult tested using high-level clicks we usually observe wave V at a latency of typically 6 ms or a little less; we know from the *threshold* ABR that peak latencies increase as the stimulus is reduced towards the audiological threshold or when lower frequency stimuli are employed (a delay associated with the travelling wave within the cochlea). For a description of the mechanisms see Burkard & Don (2012). Other factors affect latency, including age, gender, degree of hearing loss and audiometric slope (Lightfoot, 1993). Some of these factors also influence the latency difference between peaks (the inter-peak latency, IPL) though the effects of hearing loss and stimulus level on IPLs are far less than for absolute latencies (Kirsh et al. 1992). For example, the female I-V IPL is typically a little less than 4.0 ms whereas that of males is a little over 4

ms (the mechanisms of the gender difference are believed to be nerve length and core temperature). The infant I-V ILP is typically 5.0 ms at birth (full-term) (Gorga et al. 1987), reducing as myelination of the auditory pathway occurs in the first few years of life towards adult values.

The issues of patient age, physical size, and core temperature all disappear if we consider the inter-aural latency difference (ILD) of either absolute latency measurements (e.g. wave V latency) or IPLs (e.g. I-V). Here, the patient is acting as their own control but there are two important considerations:

- This approach is valid for unilateral pathologies but may be insensitive to bilateral or systemic pathologies;
- The effect of an asymmetric hearing loss (which may be unrelated to any neurological pathology) must be considered since this will result in ear-specific increases in absolute latency. For that reason, it is appropriate to apply a latency correction to cases of asymmetric hearing loss if possible.

Many abnormalities affecting the auditory neural pathway will result in changes to the nABR. Firstly, prolonged latencies (absolute and inter-peak) may be seen and secondly, desynchronization in the firing of the individual nerve fibres can result in degraded response morphology and reduced peak amplitudes; in extremis the ABR can be absent. The above abnormalities may apply to the entire waveform or only for those peaks generated medial to the site of a focal pathology. Whereas prolonged latencies can be measured, degraded morphology is more difficult to quantify.

7.4 Test and stimulus parameters

Timebase (or window, recording epoch): Since high stimulus levels are used we expect to record peak latencies less than 10 ms, even in pathological cases, so a timebase of 10-12 ms is appropriate. This shorter timebase provides greater measurement resolution for subsequent data analysis.

Stimulus repetition rate: A timebase of 12 ms would in theory allow a rate up to 83 /s to be used. However, to record the IPLs we need to record all peaks and the amplitude of wave I is known to diminish and the latencies of ABR peaks increase as the rate is increased above about 20 /s (Lightfoot, 1992). To preserve our ability to record wave I a rate below 20 /s is therefore used. The rate must not be harmonically related to the mains power frequency (50 Hz in Europe) and a rate of 11.1/s is commonly used.

Filters: Unlike the *threshold* ABR where responses close to the audiological threshold are associated with longer latencies and thus with energy below 100 Hz, there is little energy in the nABR waveform below 100 Hz. Most of the unwanted physiological noise is below 100 Hz so the use of a 100 Hz high-pass filter usefully attenuates this without reducing the amplitude of the nABR (Burkard & Don 2012). In order to record accurate peak latencies we must avoid “rounding the edges” of the peaks and a low-pass filter of 3000 Hz ensures this.

Artefact rejection (AR) level: This shall be as low as practicable in order to obtain responses with a good signal to noise ratio. Efforts should be made to reduce the muscle activity and non-patient electrical interference picked up by the electrodes. In good recording conditions it will often be possible to use an AR level of no more than $\pm 10 \mu\text{V}$ but in less favourable conditions a higher (more lax) value may be unavoidable but this will have consequences for the number of sweeps required.

Sweeps: In a very relaxed patient 2000 sweeps per waveform is usually sufficient to obtain a waveform with acceptably low residual noise but if an AR level of more than $\pm 10 \mu\text{V}$ has been used the number of sweeps must be increased. The relationship between AR level and sweeps is a square law; to end up with the same residual noise, if the AR level is doubled to $\pm 20 \mu\text{V}$ the sweeps must be quadrupled from 2000 to 8000 (Lightfoot and Stevens 2014). It is not appropriate to use a fixed number of sweeps in all cases.

Electrodes: Single-use Ag / AgCl electrodes should be placed at the vertex (Cz, non-inverting) and on the mastoid (inverting), close to the back of the pinna at the level of the meatus. The common (or guard) electrode may be placed on the forehead or, when a single-channel recording is made, the contralateral mastoid may be used. Placing the non-inverting electrode on the forehead risks recording a smaller response, thus needlessly reducing the signal to noise ratio. Placing the mastoid electrode further from the ear (as one often does for threshold ABR testing) risks reducing the amplitude of wave I. To minimise mains power interference the inter-electrode impedances should be matched and ideally $< 3 \text{ k}\Omega$. The electrode leads should where possible be grouped or twisted together to minimise electrical interference.

Stimulus type: A click of 100 μs duration shall be used since other durations will compromise calibration and have unintended consequences on the spectrum of the stimulus. The polarity of the stimulus is at the discretion of the tester but it is helpful to be aware of the issues surrounding the choice of polarity. Alternating polarity clicks are acceptable and minimise the stimulus artefact in the averaged waveform. Some believe

that the auditory nerve is activated by movement of the basilar membrane in only one direction and so argue for a single polarity click (Hall 2007). Others have noted that when wave V is indistinct or when there is more than one candidate the picture is often clarified by obtaining and comparing both rarefaction and condensation stimulus waveforms; rarefaction usually yielding clearer waves I & IV and condensation yielding a clearer wave V. Figure 3 provides an example. Once the identity of the peaks has been decided the separate polarity waveforms may be combined for analysis. Current ABR systems offer the useful facility to view the separate polarity waveforms when an alternating polarity stimulus has been used.

Stimulus level: A level of 80 dBnHL (or more if necessary overcome the effect of hearing loss) is recommended. Patients with no neurological pathology and little or no hearing loss (<50 dB HL at 4 kHz) will usually produce a clear nABR for a stimulus at 80 dBnHL. The section below on corrections for hearing loss provides details.

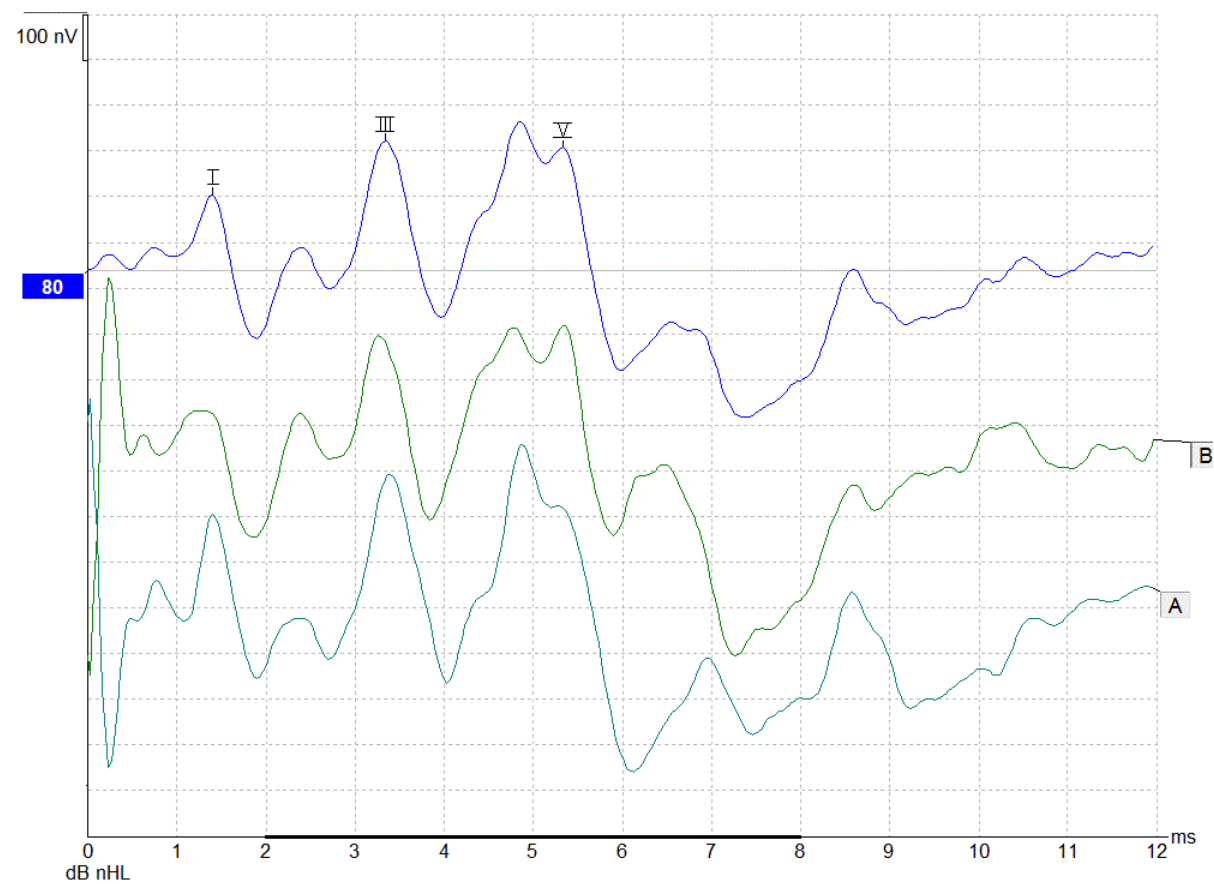


Figure 3 An example of the effects of click polarity.



The patient was a normally-hearing female in her mid-30s. Top: rarefaction & condensation waveforms combined (equivalent to alternating); middle (B): condensation; bottom (A): rarefaction. Note how the rarefaction polarity stimulus (A) gives a larger wave I but an indistinct wave V and that the condensation polarity stimulus (B) gives a less distinct wave I but a well-defined wave V. This pattern is common but is not seen in all cases.

Display aspect ratio: The vertical (voltage) scale shall be chosen to allow the features of the waveform to be seen and peak markers to be placed and inspected with minimum error. It is unlikely that a suitable aspect ratio will be outside the following range: 50-200 nV (0.05-0.2 μ V) = 1 ms.

7.5 Test procedure

Refer to sections in the main text for general recommendations. High stimulus levels are used in the nABR and the patient shall be warned to expect this but to report if any sounds are uncomfortably loud. The patient should be encouraged to physically relax their muscles, especially in their head and neck. Asking the patient to “keep still” is counter-productive because this may lead to muscle tension. Unlike the *threshold* ABR where the recording strategy is focussed on being able to determine with a high degree of confidence whether a response is present or absent, the nABR requires that precise latency measurements are made and this demands that waveforms contain a low level of residual noise. It may be necessary to record the nABR at only one stimulus level in each ear providing clear results are obtained. This allows time to ensure that high quality, low noise recordings are obtained by the selection of an appropriate AR level and number of sweeps. If objective measurements of response quality (such as Fsp) and residual noise are available these should guide the tester when it is appropriate to terminate averaging. All waveforms shall be replicated to ensure response repeatability. Replicated waveforms may be combined for analysis.

7.6 Corrections for hearing loss

Corrections for the effects of hearing loss are relatively unimportant if analysis is based on IPLs and the stimulus level is at least 80 dBnHL; there are only minor changes to IPLs with stimulus level (Kirsh et al. 1992). If waves I, III & V are not clear at 80 dBnHL then a higher level may be used if tolerated by the patient. However if absolute latency

measurements are to be used then a correction is necessary to avoid false positive results arising from prolonged latencies associated with peripheral hearing loss. There are two types of correction:

Adjustment of the measured latency to account for the expected latency prolongation associated with a cochlear loss of magnitude similar to that of the patient. It assumes that the patient has an average degree of recruitment for the extent of their hearing loss. The most popular such correction was described by Selters & Brackmann (1977). If the patient's 4 kHz hearing threshold is 50 dBHL or less then no correction is necessary. For every 10 dB the 4 kHz threshold exceeds 50 dB, 0.1 ms is deducted from the measured wave V latency. This correction is considered and if necessary applied to each ear in turn. The corrected latencies are then considered in isolation or as an inter-aural wave V calculation. With this type of correction the nABR test is conducted as normal and any correction applied in a post-hoc fashion. There have been a number of proposed variations of this method, for example see Hyde & Blair, (1981).

The stimulus levels used for the nABR test in each ear are chosen on the basis of equal loudness at 4 kHz. This makes the assumption that stimuli of equal loudness at 4 kHz will result in equal wave V latencies providing the hearing loss has no retro-cochlear component. This approach requires that an alternate binaural loudness balance (ABLB) test at 4 kHz has been conducted prior to the nABR test. In the case of quite good hearing in the better ear where the nABR will be conducted using clicks at 80 dBnHL, the better ear stimulus in the ABLB test is fixed at 80 dBHL and the ABLB test determines the level in the poorer ear that the patient judges to be of equal loudness. The nABR is then performed using this pair of stimulus levels in their respective ears. It is inappropriate to use click stimuli for the ABLB test since in a high-frequency hearing loss, the lower frequency regions of the cochlea may dominate loudness judgements whereas it is the region around 4 kHz that dominates nABR latencies (Lightfoot, 1993) so the ABLB test must be conducted at 4 kHz, using a conventional 2-channel pure-tone audiometer. This approach takes account of this patient's degree of recruitment whereas the Selters & Brackmann method assumes an average degree of recruitment.

Absolute latency measurements must not be relied on in cases of severe or profound hearing loss where the sensation level of the click stimulus is less than 10 dB (referenced to the patient's 4 kHz audiometric threshold) because in such cases, prolonged latencies are likely to occur in neurologically normal patients (Lightfoot, 1993).

7.7 Waveform analysis & results interpretation

In good recording conditions an identifiable ABR should be recordable in almost all neurologically normal patients using a click stimulus at levels down to 30 dB or less above their hearing thresholds in their mid- to high frequencies (Stevens et al. 2013). In some neurological pathologies affecting the auditory pathway, the gap between the ABR threshold and the PTA is far greater and in some cases, no ABR is recorded at all. ANSD is an example. The gap between the electrophysiological threshold and behavioural threshold has been suggested as a diagnostic test. Bush et al. (2008) proposed that a gap of more than 30 dB between a patient's ABR threshold and their click behavioural threshold was reliably seen in cases of vestibular schwannoma. This approach has the advantage of simplicity and requires no latency reference data. Rather than using the click behavioural threshold as Bush et. al. (2008) suggest, it would be more appropriate to use the 2 kHz audiometric threshold (or the average of the 2 kHz & 4 kHz PTA thresholds). This would avoid false positive outcomes in cases of steeply-sloping audiometric configurations in which subjective audition of the click is dominated by good low-frequency hearing, to which the ABR is relatively insensitive by virtue of the poor neural synchrony associated with low-frequency transient stimuli. Although this test has not been evaluated in other pathologies, the message is important: if recording conditions are good and no ABR is recorded at levels substantially above the patient's high-frequency behavioural thresholds a neurological pathology must be suspected.

In most other forms of nABR analysis the patient's ABR should be compared to reference data, preferably collected locally from neurologically normal subjects on the same equipment using the same test parameters. Whilst reference data can be used (Table 1). It is important to note that this reference data will only be valid if the same test parameters are used. Of particular importance are filters and stimulus repetition rates, which are known to affect ABR latency.

The following table is an expanded version of the reference data from a large adult study presented by Lightfoot (1992).

Variable	Gender	Mean	SD	95% CL
		(ms)	(ms)	(ms)
Wave I	both	1.79	0.28	2.34
Wave III	both	3.95	0.27	4.48
Wave V	both	5.85	0.31	6.45
I-III IPL	female	2.13	0.18	2.43
I-III IPL	male	2.22	0.22	2.58

III-V IPL	female	1.86	0.16	2.11
III-V IPL	male	1.90	0.18	2.2
I-V IPL	female	3.98	0.22	4.34
I-V IPL	male	4.12	0.2	4.46
ILD V [#]	both	0	0.19	0.37

Table 1 nABR reference data, valid only for the following test conditions: rate: 11.1/s; click polarity: 2000 rarefaction + 2000 condensation then summed (equivalent to 4000 alternating); stimulus level: 80 dBnHL (or more if required to measure the IPLs); earphones: TDH-39; amplifier filter bandpass: 100 Hz to 3000 Hz (12dB per octave). The material was 95 males and 94 female ENT patients, age range 13 to 81 years, with a variety of hearing status but no evidence of neurological disease. SD: standard deviation; 95% confidence level (CL): the upper 95% CL; [#] the ILD V assumes a correction for hearing loss has been made using either of the methods described above.

Another study (Spitzer et al. 2015) found developmental differences between ages 3–5 years, where Wave V latency continued to decrease throughout this age range. The mean latencies are within the range of expected values for adults.

Group	Wave I latency	Wave III latency	Wave V latency
Youngest (ages 3.12-8.84 yr)	1.63 (0.111)	3.87 (0.143)	5.76 (0.181)
Oldest (ages 4.67-4.99 yr)	1.63 (0.115)	3.81 (0.174)	5.57 (0.206)

Table 2: Click ABR mean latencies and SDs for wave I, III and V for 20 oldest and 20 youngest participants in the Spitzer study (Spitzer et al. 2015). Rarefaction clicks at 73dBnHL were used with 100 Hz to 1500 Hz filters, 6000 sweeps and an AR of $\pm 23.8 \mu\text{V}$.

It is conventional practice to compare a patient's latencies to the 95% CL of reference subjects. To do so anchors the specificity of each measurement to 95% but makes no guarantee of test sensitivity; one will miss pathologies having only a minor influence on the auditory pathway. Lightfoot (1992) stressed the importance of using only a single measurement to judge the nABR of an individual patient suspected of a neurological pathology; the use of multiple measurements will degrade test specificity. He suggested that nABR absence as described above should be the first step: if no ABR can be recorded, regardless of audiometric status, then the nABR cannot be used to exclude the likelihood of pathology. If the nABR is present then if the I-V IPL is available, it alone



should be used in defining nABR test outcome. Where wave I is absent and wave V is recorded the ILD V should be used.

7.7.1 Infants

The use of the nABR to detect neurological pathology in infants can be problematic; their auditory pathways will not be fully myelinated and their nABR latencies will, by adult standards, exhibit an abnormal delay.

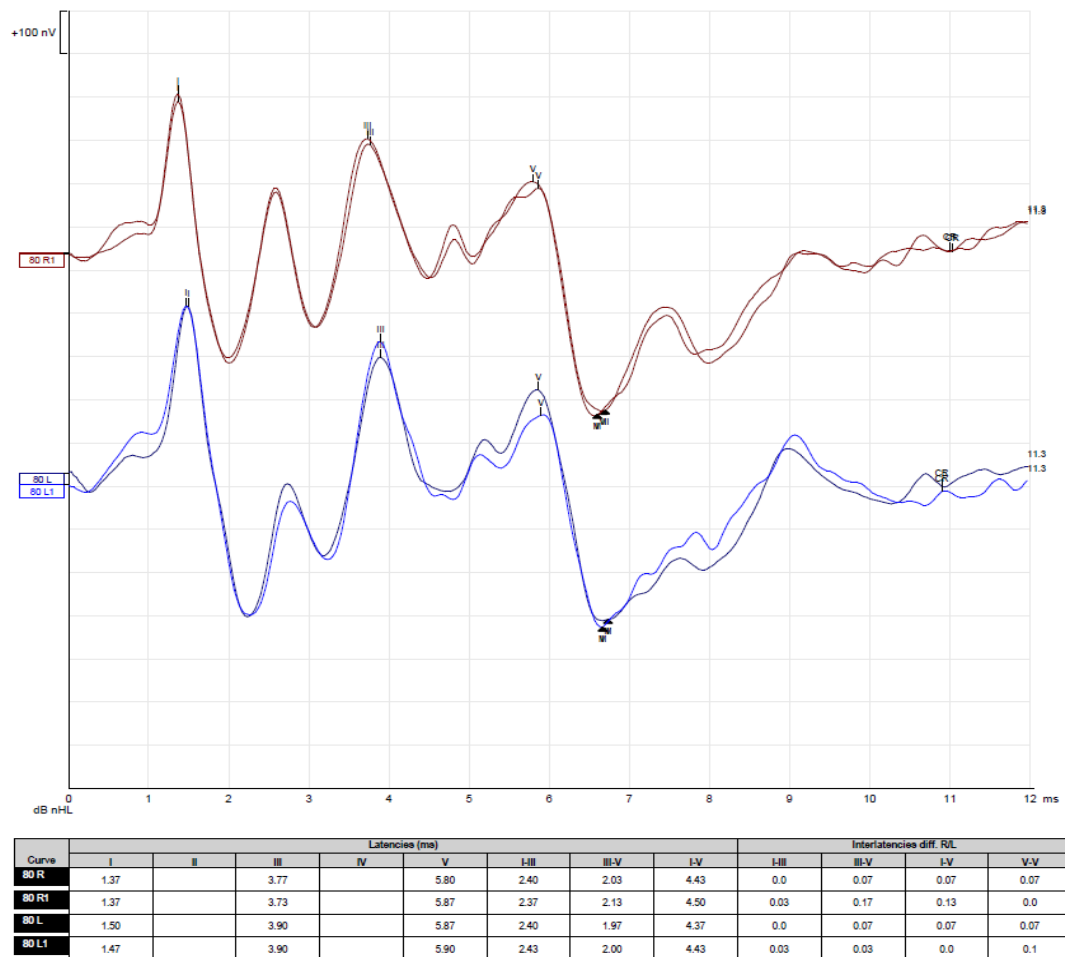


Figure 4 The nABR of a 2½ year old infant, evoked by 80dBnHL clicks presented at 11.3/s. The table shows the measured absolute and inter-peak latencies.

The I-V IPLs (around 4.4 ms) shown in figure 4 would be regarded as borderline abnormal for an adult (refer to Table 1) but were deemed to be within an acceptable

range for this 2½ year old. Note also that in figure 4 waves I and V are of similar amplitude; this is not unusual in an infant but it is rare to see this in the normal adult nABR, where wave I is almost always smaller than wave V.

The ILD V may be used but no correction for asymmetric hearing loss will be possible in newborns because no behavioural threshold will be available. Absolute latencies may be compared to age-specific reference data if available. It is likely that nABR interpretation will be limited to the assessment of gross waveform morphology and in such cases, it is particularly important to consider the medical history of the patient. For example hydrocephalus may attenuate or abolish wave V or even wave III. Figure 5 provides an example of a newborn with hydrocephalus in which only wave I is recorded.

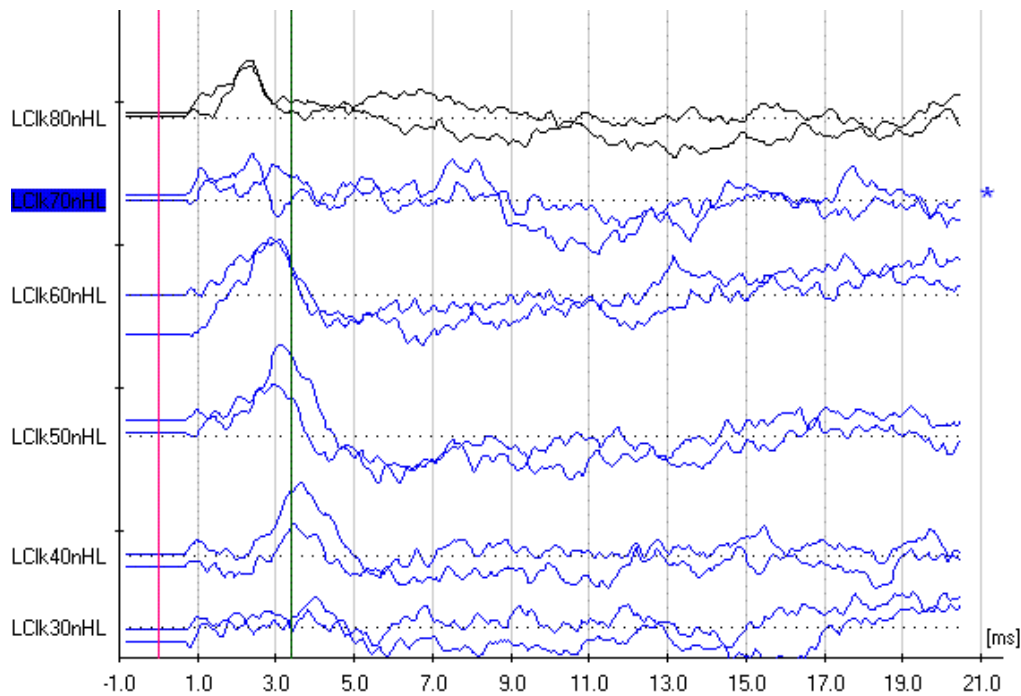


Figure 5 The nABR in a newborn with hydrocephalus. Vertical scale: 200nV/div.

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9. Appendices

9.1 Appendix A – Quick reference guide for when test conditions are not ideal

- 1) Ensure optimum test conditions e.g. impedances low, interference limited, patient is asleep where possible.

DON'T's:

Don't wake a sleeping patient (associated with excessive muscle activity).

Don't test in a noisy room.

Don't use florescent lighting, low energy lighting or light dimming controls as these can cause interference.

Don't have non-essential electrical equipment turned on. In cases where electrical interference proves to be detrimental to recording quality, attempt to limit electrical background noise levels by switching off any that is in the test room or within close proximity to the recording electrodes issue to recording quality.

DO's:

Do place equipment at least 1m away from the patient and not near any electrical trunking or power sockets.

Do physically separate leads/cabling, especially electrode / transducer / power supply leads.

Do ensure mobile phones are switched off or are in flight mode.

Do run electrode leads close together. If stimulus artefact is a problem plait longer electrode leads or use short electrode leads, gathered or twisted together.

- 2) tpABR following NHSP early guidance should be followed.
- 3) If the AR level is increased also increase the number of sweeps collected appropriately (see Fig 1); note that the relationship is not linear. If the AR level has to be relaxed above 10 μ V in order to record anything then very large number of sweeps will be necessary and this will influence test strategy (e.g. require 20 dB steps). It is usually false economy to "try a different frequency/ear"; it is better to resolve the current test than to obtain many waveforms, all of which are inconclusive.

- 4) Apply a notch filter only if this helps (notch filter should not be used when testing at 500Hz), otherwise, troubleshoot for other sources of interference.
- 5) Stimulus artefact “blocking” (flat line display option) can help reduce the effect of a large stimulus artefact at high stimulus levels but may compromise interpretation in low-frequency tpABR. This option should not be selected for CM testing.
- 6) Attempt ckABR instead of tpABR only when necessary and be aware of the limitations of this type of testing.
- 7) Maximise the available time by obtaining the most clinically crucial information first at as high a quality as possible. For example, is there any hearing?
- 8) Know when to stop. If test conditions are poor and the results are very unclear it is better to bring the patient back and try again. This approach has merit only if the problems encountered in the first session have been identified and steps taken to avoid their recurrence.

It is better to collect a few good/high quality results than many that are inconclusive or of questionable reliability.

9.2 Appendix B: Summary of recommended ABR threshold assessment parameters

	Click, NB chirp & 2 kHz / 4 kHz tone pip	0.5 kHz / 1 kHz tone pip
Electrode location	Positive : Cz or High forehead (as close to vertex as possible but avoiding fontanelle) Negative : Ipsilateral mastoid Common : Contralateral mastoid	
Stimulus type	Alternating polarity	
Stimulus timing	Click: 100µs. Tone pip: 2-1-2 cycles (linear rise–plateau–fall) or 5-cycle Blackman	
Stimulus rate	45.1 - 49.1/s 17.1 - 19.1/s for wave I on BC	35.1 - 39.1/s
Calibration values for OdBnHL	Refer to NHSP calibration data	
Amplifier reject levels	±3 to ±10 µV where possible peak-to-peak. Start at ≤±5 µV peak-to-peak. Exceed ±10 µV only after reducing interference	
Amplifier filters	Low frequency: 30 Hz High frequency: 1500 Hz	
Window length ⁴	20 ms	25 ms
Number of sweeps averaged per replication	If the artefact rejection level is ±5 µV: Typically: 2000 click & NBchirp, or 3000 for TP Minimum: 1500 click & NBchirp, or 2000 for TP If the artefact rejection level is >±5 µV see Fig 1	
Display scales	Within range 25-100 nV ≡ 1 ms See equipment specific settings.	
Display	Wave V up	

Table 3 (http://www.thebsa.org.uk/wp-content/uploads/2014/08/NHSP_ABRneonate_2014.pdf)



9.3 Appendix C: ABR corrections

	Click	Tone pip				Chirp			
		0.5kHz	1kHz	2kHz	4kHz	0.5kHz	1kHz	2kHz	4kHz
Insert phones	0	20	15	10	5	15	10	5	0
Headphones	5	20	15	10	10	15	10	5	5
Bone conductor	5	0	0	10	5	-5	-5	5	0

Table 4: Infants tested between 12 weeks and 24 weeks corrected age (85 to 168 days). Value in dB to be subtracted from the ABR nHL threshold to give eHL thresholds.

	Click	Tone pip				Chirp			
>24wk		0.5kHz	1kHz	2kHz	4kHz	0.5kHz	1kHz	2kHz	4kHz
Insert phones	5	20	15	10	10	15	10	5	5
Headphones	5	20	15	10	10	15	10	5	5
Bone conductor	5	5	5	10	10	0	0	5	5

Table 5: Infants tested between 24 weeks and 2 years (168 to 730 days) corrected age. Value in dB to be subtracted from the ABR nHL thresholds to give eHL thresholds.

	Click	Tone pip				Chirp			
		0.5kHz	1kHz	2kHz	4kHz	0.5kHz	1kHz	2kHz	4kHz
Insert earphones	5	20	15	10	10	15	10	5	5
Headphones	5	20	15	10	10	15	10	5	5
Bone conductor	5	20	15	10	10	15	10	5	5

Table 6: Children/Adults tested over 2 years (730 days). Value in dB to be subtracted from the ABR nHL thresholds to give eHL thresholds.

9.4 Appendix D: ABR Examples

1

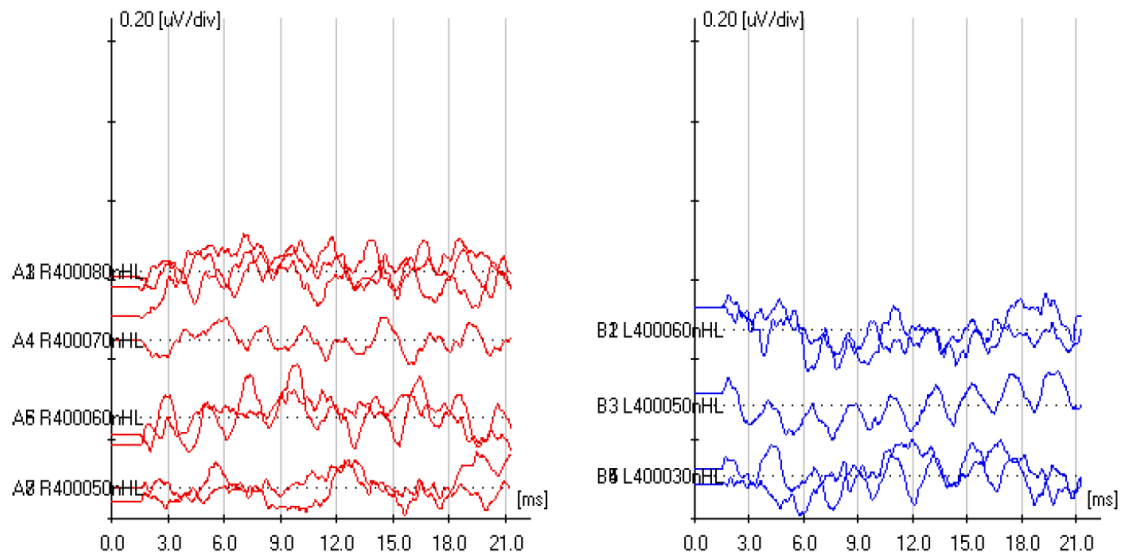


Figure 6: Sine wave interference.

The rolling sine wave is at 450Hz so probably unrelated to mains interference. It is not possible from these waveforms to establish threshold. It would be appropriate to spend time trouble shooting and attempting to eliminate the source of interference. One strategy worth trying with periodic interference is to slightly reduce the stimulus repetition rate: whatever the period of the interference, our stimulus rate should be mathematically unrelated to it.

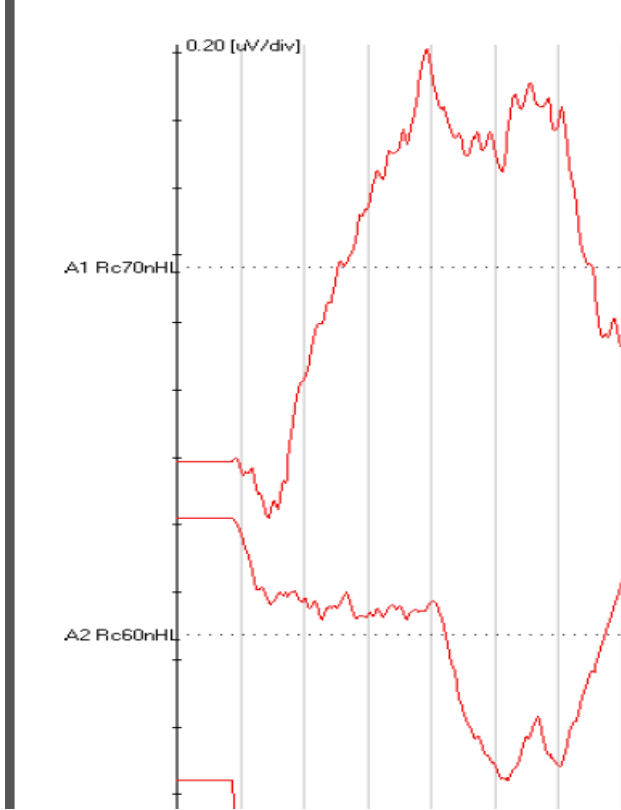


Figure 7: Difficult Test conditions in Theatre: Results are inconclusive because the waveforms are dominated by excess noise since a very lax AR level was used without an appropriate increase in the number of sweeps.

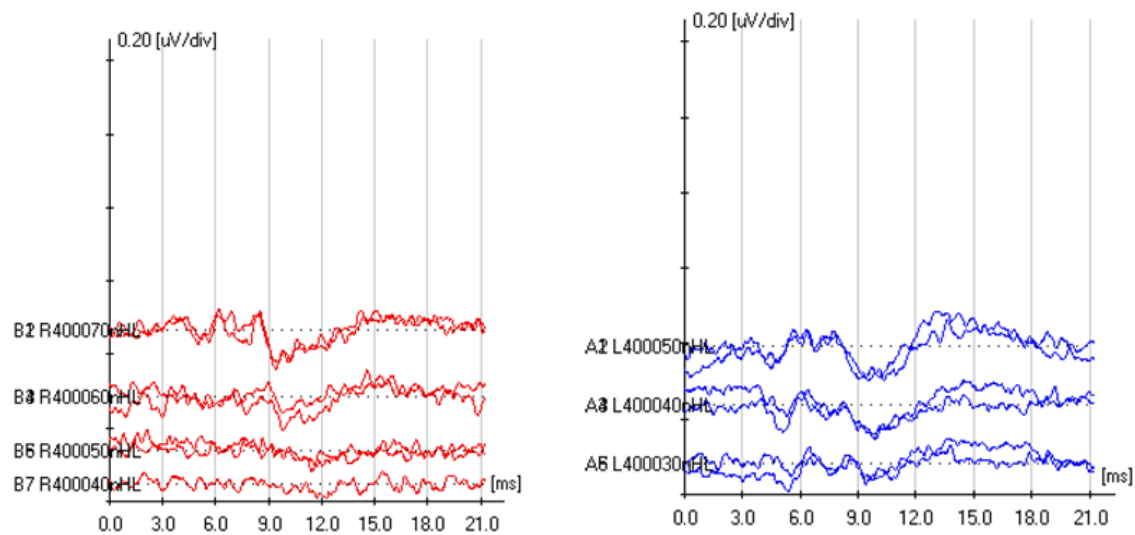


Figure 8: ABR carried out in Theatre, in good conditions

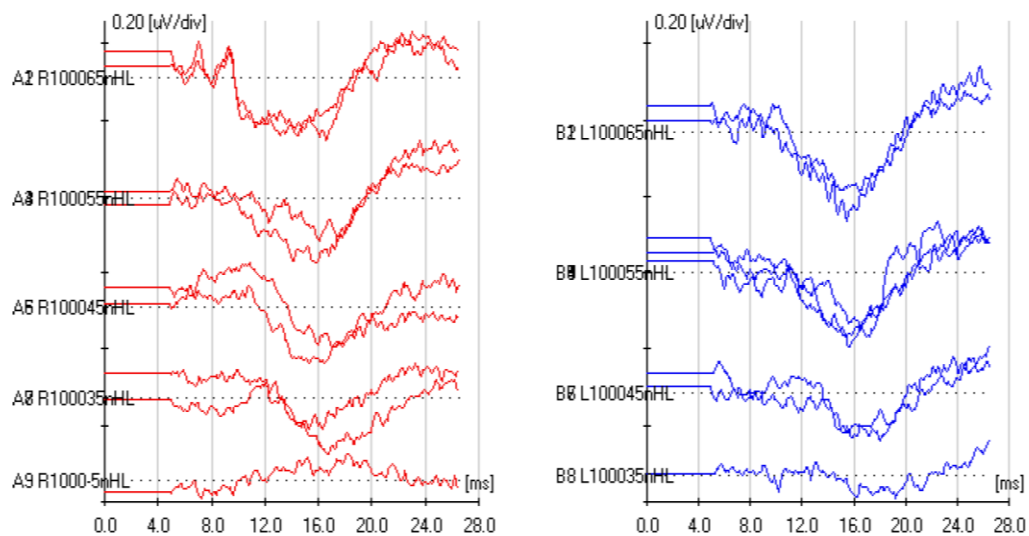


Figure 9: Repeating ABR results from an awake patient on the left. On the right only 65dBnHL can be accepted as a clear response. At lower levels there is excess residual noise and the morphology of the ABR does not follow the expected pattern.

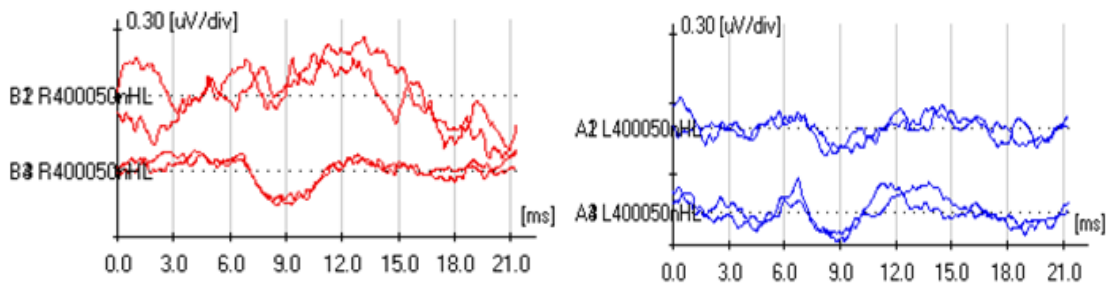


Figure 10: Notch filter used to improve quality. The upper waveforms do not have the notch noise filter applied whereas the lower waveforms do have the notch noise filter applied.