

RECOMMENDED STANDARDS FOR SHORT-LATENCY AUDITORY EVOKED POTENTIALS

I. Introduction

These Guidelines are limited to the neurologic applications of short-latency auditory evoked potentials, i.e., to the use of these responses to detect and approximately localize dysfunctions of the auditory pathways within the auditory nerve and brainstem. The audiologic applications of these potentials, some of which require the utilization of frequency-specific stimuli to assess and quantify hearing function, are excluded from consideration.

II. Terminology: Definitions, Abbreviations, and Designation of Components

Short-latency auditory evoked potentials (SAEPs) are electrical responses of the auditory pathways that occur within 10—15 ms of an appropriate acoustic stimulus in normal subjects. This generic term encompasses two categories of events: the “electrocochleogram” and the “brainstem auditory evoked potentials.”

The electrocochleogram (ECochG) consists of electrical responses of the cochlea and the auditory nerve to acoustic stimulation. These include (1) the cochlear microphonics; (2) the summing potential; and (3) the auditory nerve compound action potential (AP). The *cochlear microphonics* (CM) and the *summing potential* (SP) are receptor potentials of cochlear hair cells. The *auditory nerve compound AP* is the whole-nerve AP generated by primary auditory nerve fibers.

BAEPs are responses of the auditory nerve, brainstem, and, perhaps, higher subcortical structures to acoustic stimulation. Most of its components appear to arise from multiple sources, preventing a simple one-to-one correspondence between potential generators and individual BAEP waves.

Both terms, “electrocochleogram” and “brainstem auditory evoked potentials,” are somewhat inappropriate in that (1) the most prominent component of the “electrocochleogram,” i.e., the AP, does not arise from the cochlea but from primary auditory nerve fibers; (2) the first component of the “brainstem auditory evoked potentials” does not arise in the brainstem but in the auditory nerve; and (3) the latest components may (Legatt et al., 1988) or may not (Moller, 1988) originate, at least in part, above the brainstem. In spite of these objections, both terms are recommended as standard terminology because they are widely used and understood by all in the field. The detection of the ECochG requires special techniques such as recordings from the external auditory meatus. In these circumstances, the main ear canal-negative component of the auditory nerve compound AP should be labeled N1 (Fig. 5, top) and the subsequent negative wave N2 (Fig. 5, bottom). In ordinary recordings between vertex and earlobe or mastoid electrodes, the “vertex-positive” components of BAEPs should be designated by the Roman numerals I through VII and “vertex-negative” components following each

¹ This topic was previously published as Guideline 9.

vertex-positive wave should be labeled I' through VI'. It should be noted that the terms "vertex-positive" and "vertex-negative" only imply positivity of one electrode (at the vertex) *relative* to another electrode (over the earlobe or mastoid process) and should not be construed as indicative of the polarity of each electrical event. The limitations of this polarity designation are evident in the labeling of the earlobe-negative wave I of BAEPs as a "vertex-positive wave." It is also suggested that for the sake of brevity the designation "wave V" be applied to this wave whether or not it is preceded by a barely discernible wave IV.

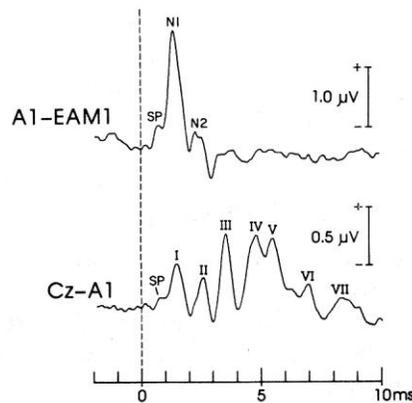


FIG. 5. Top: Auditory nerve compound AP recorded by a non-invasive external auditory meatus electrode. Bottom: BAEPs. Responses were obtained simultaneously on an audiometrically normal volunteer. Stimuli consisted of alternating rarefaction and condensation broad-band clicks, delivered to the right ear at 8/s and 120 dB pe SPL with masking of the contralateral ear by white noise at 60 dB SPL. Zero in the time calibration indicates onset of the electrical waveform of the click. (From G. E. Chatrian, unpublished data.)

III. Stimulus

It is recommended that "broad-band" clicks, the acoustic energy of which is spread over a wide range of audio frequencies, be used for the neurologic applications of auditory evoked potentials. These clicks should be generated by driving with a 100 usec rectangular pulse (single monophasic square wave), a standard audiometric earspeaker having a relative flat frequency spectrum. For special purposes, such as intraoperative recording, the clicks can be delivered through ear inserts. The sound pressure waves so produced consist of a first and major wave, followed by smaller, highly damped oscillations of alternating polarity that may last up to 2 msec or longer. The waveform of the driving pulse, to be referred to as the click's "*electrical waveform*," can be viewed by displaying on an oscilloscope screen, the output of the pulse generator (Fig. 6, top

waveforms). The sound pressure waves, to be designated the click's "*acoustical waveform*," can be examined by coupling the earspeaker to the microphone of a "sound level meter" via a standard "earphone coupler" or "artificial ear" and displaying the meter's electrical output on an oscilloscope screen (Fig. 6, bottom waveforms). To the extent that the artificial ear approximates the acoustic transfer characteristics of the human external auditory meatus, this acoustic wave-form resembles the stimulus applied to the tympanic membrane.

Many other types of acoustic stimuli are used for eliciting BAEPs, such as tone bursts, tone pips, filtered clicks, single-cycle clicks, etc. Most of these stimuli have frequency spectra that are more restricted than those of broad-band clicks, i.e., they are "narrow-band" stimuli best suited for audiological applications of BAEPs.

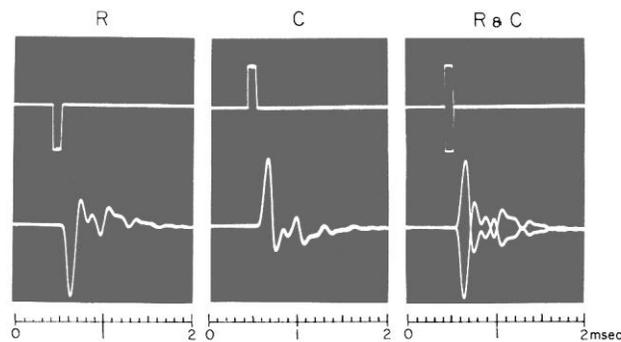


FIG. 6. Electrical (**top**) and acoustic (**bottom**) waveforms of rarefaction (R), condensation (C), and alternating (R and C) clicks (1).

Stimulus Polarity

The polarity of the first and most prominent wave of the acoustic waveform of the click (as distinct from that of the electrical pulse driving the earspeaker) determines whether a negative or positive pressure is applied in front of the earspeaker diaphragm. Those clicks in which the first and major acoustic wave applies negative pressure in front of the earspeaker diaphragm are referred to as *rarefaction* clicks (Fig. 6, R). Those clicks in which the first and most prominent acoustic wave applies a positive pressure in front of the earspeaker diaphragm are referred to as *condensation* clicks (Fig. 6, C). It should be recognized that these polarity designations are, to some degree, arbitrary, since acoustical polarity is sometimes reversed during transfer through the ear canal. Click generators must be capable of delivering rarefaction only, condensation only, and alternating rarefaction and condensation (Fig. 6, R and C) clicks. For tone pips, a polarity designation is meaningless.

In certain pathologic conditions associated with severe, steep high-frequency hearing loss, BAEPs elicited by rarefaction clicks may differ in latency and, to a degree, in morphology from BAEPs evoked by condensation clicks (Coats and Martin, 1977). In these circumstances, using clicks of alternating polarity results in poorer resolution of the response than using either rarefaction or condensation clicks alone. This problem is obviated by using rarefaction only, condensation only, or separate rarefaction and

condensation clicks. There is no clear rationale for preferring rarefaction over condensation clicks, or vice versa. However, it is essential that normative data be collected using the stimulus polarity or polarities to be utilized in clinical testing. Summating the responses elicited by separate rarefaction and condensation clicks reduces stimulus artifact and is acceptable whenever no substantial differences exist between responses to separate rarefaction or condensation stimuli.

Abnormally increased latency differences between responses to rarefaction and condensation stimuli should not be interpreted as evidence of retrocochlear dysfunction (i.e., dysfunction of the auditory pathways at the auditory nerve, brainstem, or higher levels unless cochlear dysfunction has been ruled out by formal audiometric testing).

Stimulus Rate

Stimulus rates employed vary widely from 5 to 200/s. depending on test applications. Waves I,II, VI, and VII are particularly reduced in amplitude at rates higher than 10/s. Thus, stimulus rates of 8—10/s are especially suited to resolve these peaks. (However, cf. Section VIII, “Recording at High Stimulus Rates”).

Stimulus Intensity

It is recommended that click intensity be acoustically *calibrated* in “decibels peak-equivalent sound pressure level” (dB pe SPL). Sound pressure level measurements use as a reference level (0 dB) 20 micropascals (Pa), which equal $0.0002 \text{ dyne}^2/\text{cm}^2$. A click’s pe SPL is the SPL of a pure tone, the peak-to-peak amplitude of which matches the peak-to-peak amplitude of the click’s acoustic waveform (Chatrian et al., 1982). The calibration of the stimulus delivery system should be repeated at least every 6 months. Each laboratory should be capable of converting its intensity measures into equivalent values obtained with other methods, i.e., expressed in “decibels above normal hearing level” or dB HL (dB above the average hearing threshold of a group of normal young adults tested by the same laboratory under conditions identical to those used for recording BAEPs clinically) or in “decibels above sensation level” or dB SL (dB above the subject’s individual hearing threshold in the ear tested). Stimulus intensities employed generally range between 40 and 120 dB pe SPL.

Monaural Versus Binaural Stimulation

Click should be delivered monaurally, i.e., to one ear at a time (Stockard et al., 1978).

Contralateral Masking

It is recommended that the contralateral (nonstimulated) ear be masked by white noise at 60 dB SPL to eliminate “crossover” responses, i.e., bone-conducted responses originating in this ear. Although not necessary in every situation, it is recommended that contralateral masking be included in the routine test protocol to avoid its inadvertent omission when it is required. For a description of the instrumentation and procedure for

² A dyne is the force necessary to give acceleration of 1 cm/s to 1 g of mass.

calibrating the masking noise as well as the click stimulus, see Chatrian et al. (1982).

IV. Recording

System Bandpass

The recommended system bandpass for BAEP recording is 10-30 to 2,500-3,000 Hz (-3 dB) with a filter rolloff not exceeding 12 dB/octave for the low frequencies and 24 dB/octave for the high frequencies. Whenever this test is performed in the presence of irreducible EMG and mechanical artifacts, the low-frequency cutoff may be raised to 100-200 Hz. However, this last cutoff is not advisable for testing children (Stapells, 1989). A high-frequency cutoff of 1,500 Hz is acceptable for intraoperative BAEP (but not ECoG) monitoring.

Stimulus Artifact

The use of properly electrostatically and electromagnetically shielded stimulus delivery systems is suggested to attenuate or eliminate the stimulus artifact, especially when using rarefaction-only or condensation-only clicks.

Analysis Time

An analysis time of 10-15 ms from stimulus onset is suggested. An analysis time of no less than 15 ms is sometimes required to demonstrate extremely delayed responses in certain pathologic conditions. Analysis times of 15 ms are also essential for neonatal and intraoperative recordings.

Number of Trials to be Averaged

It is suggested that about 1,000-4,000 individual trials be averaged until good waveform resolution has been achieved. Two or more responses must be obtained and superimposed to demonstrate replicability or lack of replicability of their components.

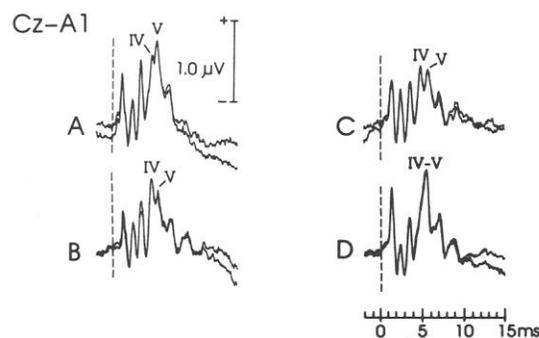


FIG. 7. BAEPs of four audiometrically normal volunteers. Monaural click stimulation at 8/s and 120 dB pe SPL and recording between vertex and ipsilateral earlobe (Cz—Ai). Note variable relationship between waves IV and V. (From G. E. Chatrian, unpublished data.)

Electrode Placement

It is recommended that recording electrodes be placed as follows: (1) on the scalp at the vertex (Cz position of the 10-20 International System of EEG electrode placement) and (2) over the left and right earlobes (auricular) A1 and A2 positions of the 10-20 System) or the left and right mastoid processes (M1 and M2).

The ground electrode may be placed anywhere on the body. For convenience, it is recommended that it be placed on the head, for instance, on the scalp in a midline frontal location (position Fz of the 10-20 System). Electrode impedances must be < 5 KOhms.

Montage

A montage consisting of the following derivations is suggested for BAEP recording:

Channel 1: Vertex-ipsilateral earlobe or mastoid (Cz-Ai or Mi)

Channel 2: Vertex-contralateral earlobe or mastoid (Cz-Ac or Mc)

In vertex-ipsilateral earlobe derivations, the relationships of waves IV and V (the “IV-V complex”) are very variable even in normal subjects (Chiappa and Gladstone, 1979). Wave IV may appear as a wavelet on the ascending limb of wave V (Fig. 7, A). Less commonly, wave V may consist of a wavelet on the descending limb of wave IV (Fig. 7, B). In some subjects, both waves IV and V may be well developed (Fig. 7, C). In other individuals, wave IV may be absent (Fig. 7, D). Vertex-contralateral earlobe or mastoid derivations generally demonstrate better separation of waves IV and V (Fig. 8). Thus, they are helpful in confirming the identity of waves IV and V detected in vertex-ipsilateral earlobe or mastoid reference derivations and are sometimes essential to identify them (Stockard et al., 1978; Chiappa and Gladstone, 1979).

State of Consciousness

BAEPs can be obtained during either wakefulness or sleep. Sedation may occasionally be indicated with very young or tense patients, but now requires special provisions in most facilities. In recording patients who are comatose or are undergoing surgery, consideration must be given to the fact that hypothermia may produce BAEP alterations indistinguishable from those caused by structural lesions of the auditory pathways (Markand et al., 1987).

Neonates and Children

The BAEPs of neonates and infants have peculiar features and require special recording techniques (Picton et al., 1986; Stapells, 1989). Age-specific norms must be used for BAEP studies in subjects younger than 3 years.

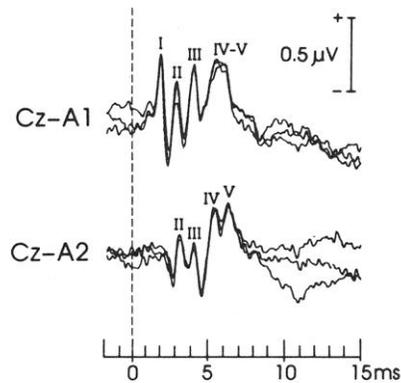


FIG. 8. BAEPs of audiometrically normal volunteer. Monaural click stimulation of 8/s and 120 dB pe SPL and recording between vertex and ipsilateral earlobe (top trace) and vertex and contra-lateral earlobe (bottom trace). (From G. E. Chatrian, unpublished data.)

V. Analysis of Results

Records are analyzed primarily for the presence of waves I, III, and V.

Measurements

Measurements must include the following: (1) wave I peak latency; (2) wave III peak latency; (3) wave V peak latency; (4) I-III interpeak interval; (5) III-V interpeak interval; (6) I-V interpeak interval; (7) wave I amplitude; (8) wave V amplitude; and (9) wave IV-V/I amplitude ratio.

Peak latencies, i.e., absolute latencies, must be measured from the leading edge of the driving pulse (electrical waveform of the click) indicated in the recording by the onset of the artifact, if any. Peak amplitudes are measured from the prestimulus baseline (when one is available) or from the immediately preceding or following peak of opposite “polarity.”

VI. Criteria for Clinically Significant Abnormality

In most laboratories, it is customary to interpret as abnormal peak latencies, interpeak intervals, and amplitude ratios that are beyond 2.5 or 3 standard deviations from the mean of an age-matched control sample from the normal population. The implications of the choice of limits of normality, the inapplicability of the standard deviation as a measure of dispersion for values that do not conform to a normal (gaussian) distribution, the limitations inherent in the use of the standard deviation for comparing results obtained in individual patients to population norms, and the possible use of alternative measures, especially tolerance limits (Fig. 8), are discussed in the introductory section of

“Recommended Standards for Visual Evoked Potentials.”

Abnormal BAEP measures do not necessarily imply altered retrocochlear function. At present, criteria for *retrocochlear dysfunction* include the following.

1. Absence of all BAEP waves I through V. unexplained by extreme hearing loss determined by formal audiometric testing.
2. Absence of all waves following waves I, II, or III.
3. Abnormal prolongation of I-III, III-V. and I-V interpeak intervals. I-III or III-V intervals can sometimes be abnormally prolonged even in the face of a normal I-V interval.
4. Abnormal diminution of the IV-V/I amplitude ratio, especially when accompanied by other abnormalities.
5. Abnormally increased differences between the two ears (interaural differences) as regards the I-III, III-V, and I-V interpeak intervals, when not explained by unilateral or asymmetric middle and/or ear dysfunction determined by appropriate audiometric tests.

The importance of obtaining formal audiometric testing in patients undergoing BAEP examination is emphasized by the consideration that the proper application of two of five criteria of BAEP abnormality (Nos. 1 and 5) requires knowledge of the patient’s audiogram.

There are at present insufficient data to justify interpreting any BAEP alterations not listed above as suggestive of retrocochlear dysfunction.

A concept that is sometimes not fully appreciated is that hearing impairments frequently are of mixed origin. Thus, the hearing loss of patients with lesions of the auditory nerve or brainstem may well include deficits of conductive, cochlear, or higher cerebral origins. For example, posterior fossa lesions may also cause cochlear dysfunction by interfering with blood supply to the cochlea (Legatt et al., 1988). Pure tone audiometry is necessary to understand these combined disorders and their influences on BAEPs.

VII. Minimal Test Protocol

It is recommended that, for neurologic applications, minimal BAEP testing should consist of responses to rarefaction, condensation, or summated separate rarefaction and condensation clicks delivered monaurally at intensities of 90—120 dB pe SPL, preferably 115 or 120 dB pe SPL and at rates preferably below 25/s. The contralateral ear should be masked by white noise at 60 dB SPL.

VIII. Desirable Additional Techniques: Description, Protocol, and Rationale

In certain circumstances, especially in individuals with severe hearing deficits, wave I is too small in amplitude to be clearly detected by surface earlobe or mastoid electrodes. Because this potential is an essential benchmark for BAEP measurement, it is important that some technique be available for recording it from a location closer to its source, the auditory nerve. An external auditory meatus (EAM) placement is recommended. A “plastic-leaf” electrode (Coats, 1974; Chatrian et al., 1982) that places a silver ball within

2-4mm of the tympanic membrane or a needle electrode inserted under the skin of the ear canal (Yoshie and Yamaura, 1969) may be used for these recordings. The introduction of “transtympanic” electrodes that penetrate the tympanic membrane and come to rest against the promontory of the middle ear requires specialized otologic skills and is not recommended for neurologic studies except for intraoperative recording. Because impedances of EAM electrodes may be high, preamplifiers with sufficiently high input impedances must be employed for recording from the EAM.

Montage

A montage consisting of the following two derivations is recommended for a two-channel system:

Channel 1: Ipsilateral earlobe or mastoid-ipsilateral external auditory meatus (Ai or MiEAMi)

Channel 2: Vertex-ipsilateral auricular (earlobe) or mastoid (Cz-Ai or Mi). This montage makes it possible to detect wave N1 of the ECoChG in channel 1 and BAEPs in channel 2. Wave N1 of the ECoChG is the main component of the auditory nerve compound AP. This wave is the same potential that is termed wave I in BAEP records, but generally greatly exceeds it in amplitude. When only one recording channel is available, we recommend the following derivation that combines ECoChG and BAEP potentials:

Vertex-ipsilateral external meatus (Cz-EAMi).

Protocol

Simultaneous ECoChG and BAEP testing is conducted under the same conditions described for recording BAEPs alone.

Measurements

In addition to the measurements described in Section V, “Analysis of Results,” the following measurements are recommended: (1) NI peak latency; (2) NI-III interpeak interval; and (3) NI-V interpeak interval.

These measurements may add to or replace those of wave I latency, and I-III and I-V interpeak intervals. It should be noted that the amplitude of NI is influenced to a major degree by the position of the recording electrode in the EAM. Thus, interaural NI amplitude differences should receive little consideration.

Recording of Multiple Intensities

Reduction in stimulus intensity primarily causes latency prolongation of individual response components without major alteration of interpeak intervals (Fig. 6). Whenever BAEP, or combined ECoChG-BAEP, recording at a single stimulus intensity produces evidence of a retrocochlear disorder, confirmatory information can be obtained by recording at other, usually lower, intensities.

Test Protocol

It is recommended that BAEPs or combined ECochG-BAEPs be recorded at progressively lower intensities from 120 dB pe SPL to below the electrophysiologic threshold, i.e., an intensity at which no BAEP wave is detectable any longer. Ideally, this should be accomplished in steps of 10 dB. However, for clinical testing it is more practical to descend in 20-dB steps and subsequently to ascend to fill in the gaps, if time permits. Two coherent averages should be obtained at least at the highest and at near threshold intensities.

Measurement and Plotting of Latency-Intensity (Input-Output) Functions

Measurements to be made include the following: (1) wave I (or N1) peak latency; (2) wave III peak latency; (3) wave V peak latency; (4) I (or N1)-III inter-peak interval; (5) III-V interpeak interval; (6) I (or NI)-V interpeak interval; and (7) BAEP threshold, approximated by taking the midpoint between the lowest intensity at which BAEPs, usually wave V, are detected and the highest intensity at which BAEPs are no longer demonstrated.

Measurements 1-6 above are plotted on a graph as a function of stimulus intensity and the individual points are joined by a line. “*Latency/intensity*” (“*input-output*”) functions are thus obtained for each of the six parameters examined (Fig. 9). Comparing to normal standards measures obtained at multiple intensities rather than at a single intensity greatly increases the confidence of the interpretation (Coats and Martin, 1977; Coats, 1978). Measurement of BAEP thresholds to broadband clicks do not replace formal pure tone audiometry.

Recording at High Stimulus Rates

Recording BAEPs at stimulus rates of 50—70/s facilitates the rapid identification of wave V in screening studies of neonates and infants as well as adults.

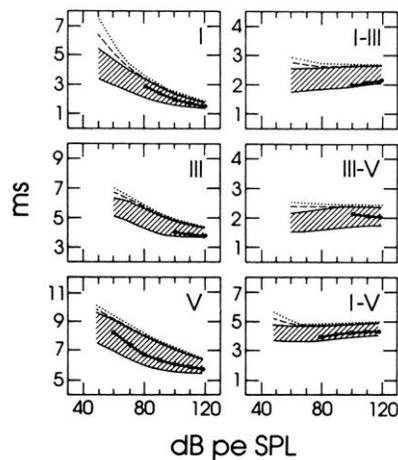


FIG. 9. Latency/intensity (LI) functions for waves I, III, and v of BAEPs and their interpeak intervals. Same subject as in Fig. 1. Limits of shaded areas represent 2 standard deviations from the mean of an age-matched control sample from the normal population, and dashed lines represent the 95% and 99% tolerance limits for 95% of the normal population. (From G. E. Chatrian, unpublished data.)

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