Education

Clinical Note

Brainstem Auditory Evoked Potentials in Neonates and Pediatrics

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Abbreviations

ACNS	American Clinical Neurophysiology Society
ABR	Auditory Brainstem Response
AER	Auditory Evoked Response
BAER	Brainstem Auditory Evoked Response
BAEP	Brainstem Auditory Evoked Potential
CMRR	Common Mode Rejection Ratio
CNS	Central Nervous System
EEG	Electroencephalography
EP	Evoked Potential
ICU	Intensive Care Unit
NICU	Neonatal Intensive Care Unit
SEP	Somatosensory Evoked Potential
VEP	Visual Evoked Potential

Tags

ACNS	BAER	EP	NICU
AEP	BAEP	Electrodiagnostic Assessment	SEP
AER	EEG	ICU	VEP

1. Introduction

Evoked potential (EP) is an electrophysiological diagnostic test that records the neural responses over various parts of the nervous system in response to stimulation.[1,2] Each stimulation generates evoked responses which are time-locked to the stimulus and low in amplitude compared to electroencephalography (EEG) and environmental noise.[2] Averaging of many evoked responses is essential to amplify these low amplitude responses and obtain a reliable EP. [2] In clinical practice, there are three types of EP used routinely: auditory, visual and somatosensory. [2] Each type of EP assesses a series of waveforms or peaks which occur at different latencies, from a few milliseconds to a few hundred milliseconds.[2,3] Analysis of EP latencies, amplitudes and side-to-side differences are used to assess the abnormality of the test results.[1] Numerous journal articles and textbooks have well documented the clinical application of EP in adults. This paper aims to discuss the auditory EP testing and clinical applications in neonates and pediatrics.

2. Brainstem Auditory Evoked Potentials

2.1 Clinical and Anatomy

Brainstem auditory evoked potentials (BAEPs), also known as brainstem auditory evoked responses (BAERs) or auditory brainstem responses (ABRs), are electrical signals generated by the brainstem auditory structures. [1,2] BAEPs are a type of short-latency auditory evoked potentials (AEPs). They consist of a series of waves (wave I to VII) that typically occur within 10ms after stimulus onset.[1,2] Wave I to V are of clinical significance to assess peripheral auditory nerve function, such as infant hearing assessment for hearing loss or impairment, and for detecting central nervous system (CNS) lesions or disorders, typically showing abnormalities in disorders affecting the auditory portion of cranial nerve VIII.[4] Figure 1 illustrates a typical BAER waveform using three different montages, by using three electrodes recording the two earlobes (i.e., A1 and A2) and Cz electrode placement at midline of central region.[5] Table 1 and Figure 2 present the known and potential generators of each wave, also known as peak.[5,6,7]

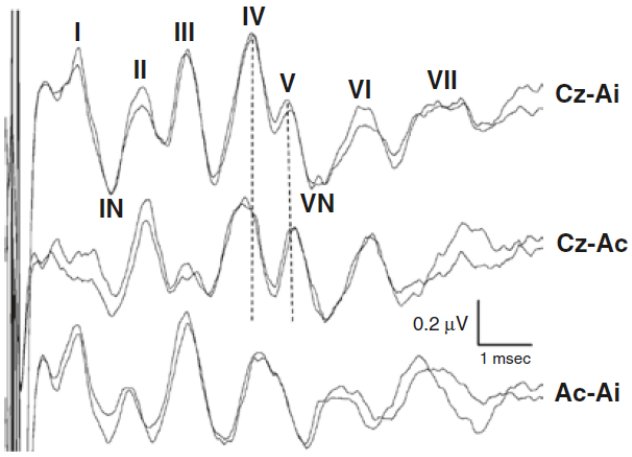


Figure 1. A BAER recorded on three different derivations using three electrodes (A1, A2 and Cz), demonstrating wave I-VII on the ipsilateral auricular (Ai) recording and wave II-V on the contralateral

auricular (Ac) recording. In practice, multiple derivations can be recorded concurrently to optimize diagnostic yield and comparison. Adapted from Principles of neurophysiological assessment, mapping, and monitoring (Second edition) (p. 148), by Davis, S. F., & Kaye, A. D. (2020).

Table 1. BAER Waveforms and Their Associated Physiological Generators. Adapted from *Clinical neurophysiology* (3rd ed) (p.477), by Daube, J. R., & Rubin, D. I. (2009).

Wave	*Generator*
I	Proximal acoustic nerve (segment near cochlea)
II	Distal acoustic nerve (segment near brainstem) or cochlear nuclei
III	Superior olive and projections to the lateral lemniscus; medial nucleus of trapezoid body might generate a part of wave III
IV	Most likely the lateral lemniscus, but data is not definitive
V	High pontine or lower midbrain structures: probably the lateral lemniscus, inferior colliculus, or a combination thereof
VI	Most likely the medial geniculate nucleus or projections from the inferior colliculus
VII	Most likely the auditory radiations to primary auditory cortex

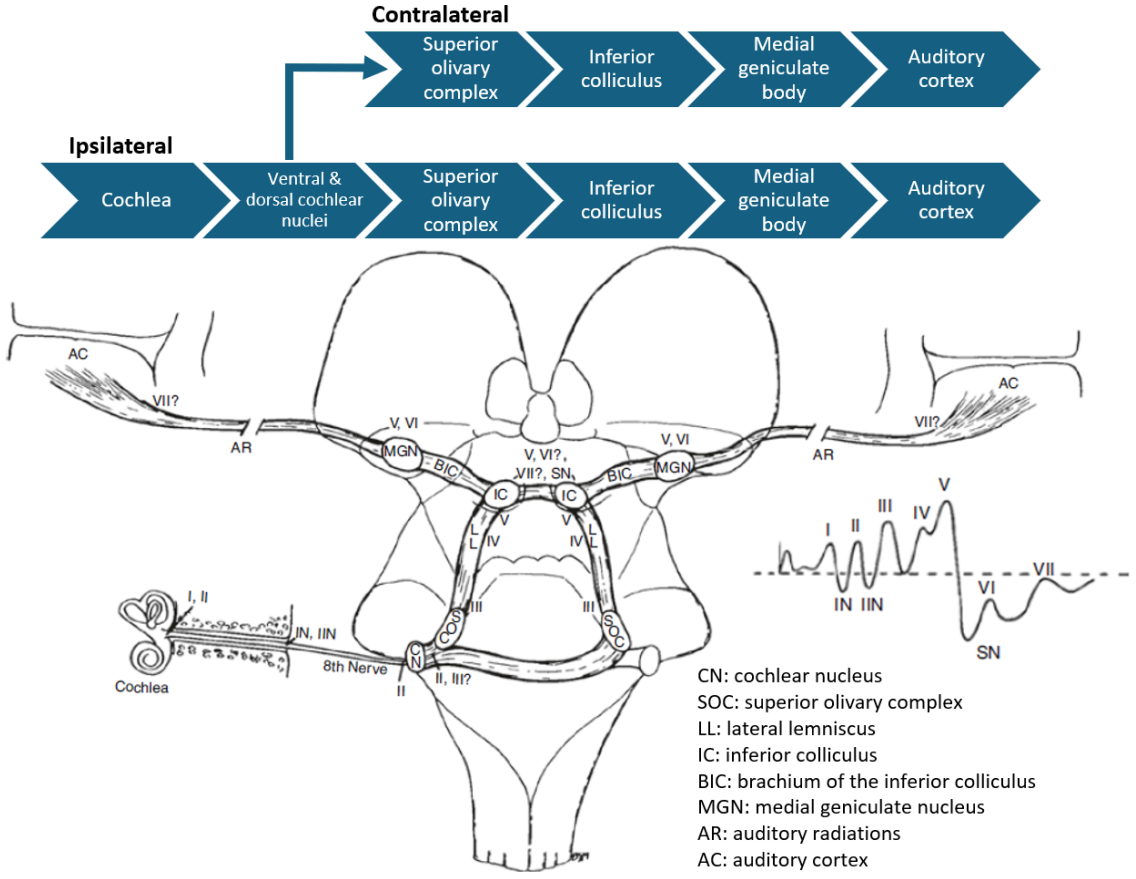


Figure 2a. A diagrammatic overview of the auditory pathway beginning at the cochlea and neuroanatomy of associated generators within the brainstem of BAER, each wave is depicted with corresponding roman numeral. Modified from Principles of neurophysiological assessment, mapping, and monitoring (Second edition) (p. 148), by Davis, S. F., & Kaye, A. D. (2020).

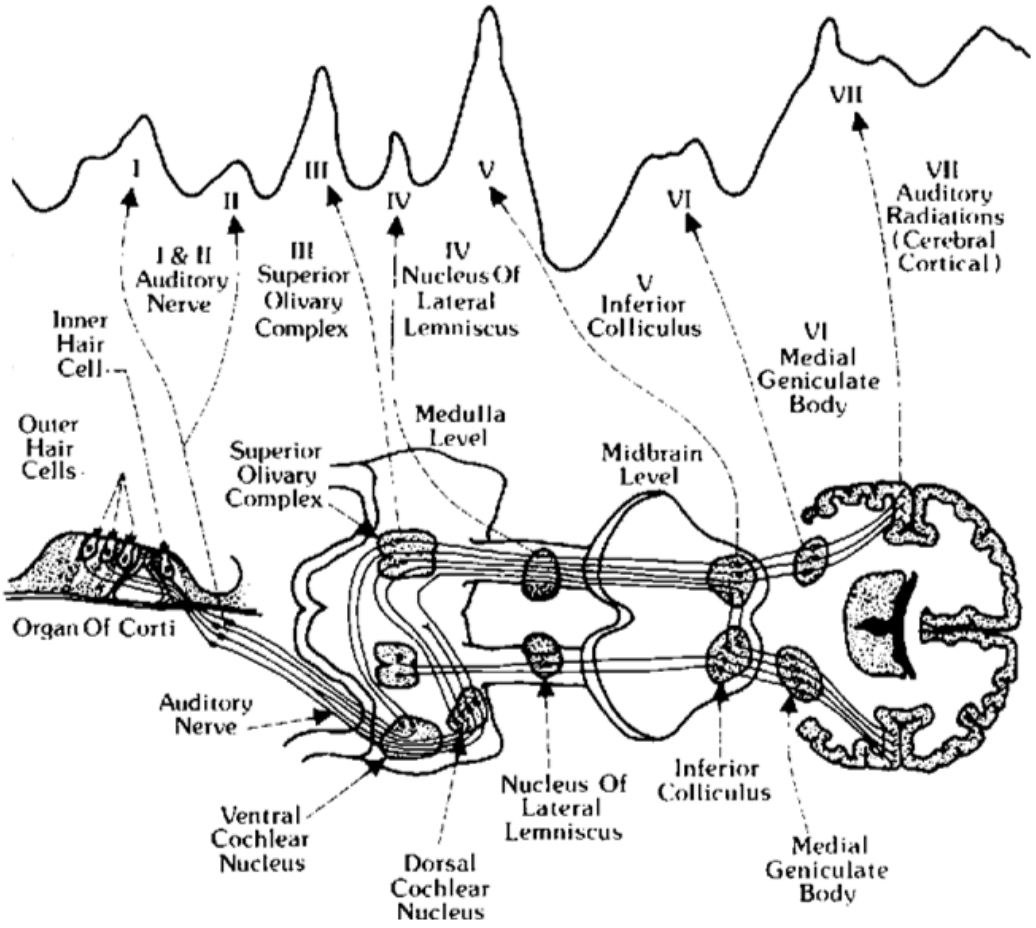


Figure 2b. An illustration of a normal BAER and its corresponding generators within a brainstem cross-section. Adapted from Brainstem evoked response audiometry. The Annals of otology, rhinology, and laryngology (p.183–186), by Giroux, A. P., & Pratt, L. W. (1983).

The brainstem auditory pathway is structurally established by around 26 weeks of gestation and undergoes rapid development afterward.[10] BAER can first be detected at approximately 26 weeks, becoming more consistent and reliable by 28 weeks.[10] From this stage, BAER demonstrates significant maturation leading up to full-term birth, with further, slower development continuing throughout infancy.[10]

Among the recorded waveforms, waves I, III, and V are the most consistent and clearly identifiable.[10] In contrast, waves II, VI, and VII are often too variable for reliable analysis, and wave IV may merge with wave V in some cases.[10] The latency of the key waves (I, III, and V) decreases as gestation progresses, with the most pronounced changes occurring in the weeks before 34 weeks of gestation.[10] Although maturation continues after birth, it proceeds at a slower pace and extends up to roughly 2 to 4 years of age.[10] Figure 3 depicts developmental changes in the III–IV and IV–V interpeak latencies and distinct maturational patterns.[11] Intervals associated with axonal conduction (III–IV and I–II) reach adult-like timing by term birth, while intervals

influenced by synaptic transmission (IV–V and II–III) continue to mature postnatally.[11] Wave IV shows early stability when present, whereas wave V and wave III remain delayed into infancy, reflecting prolonged synaptic development in central auditory pathways.[11]

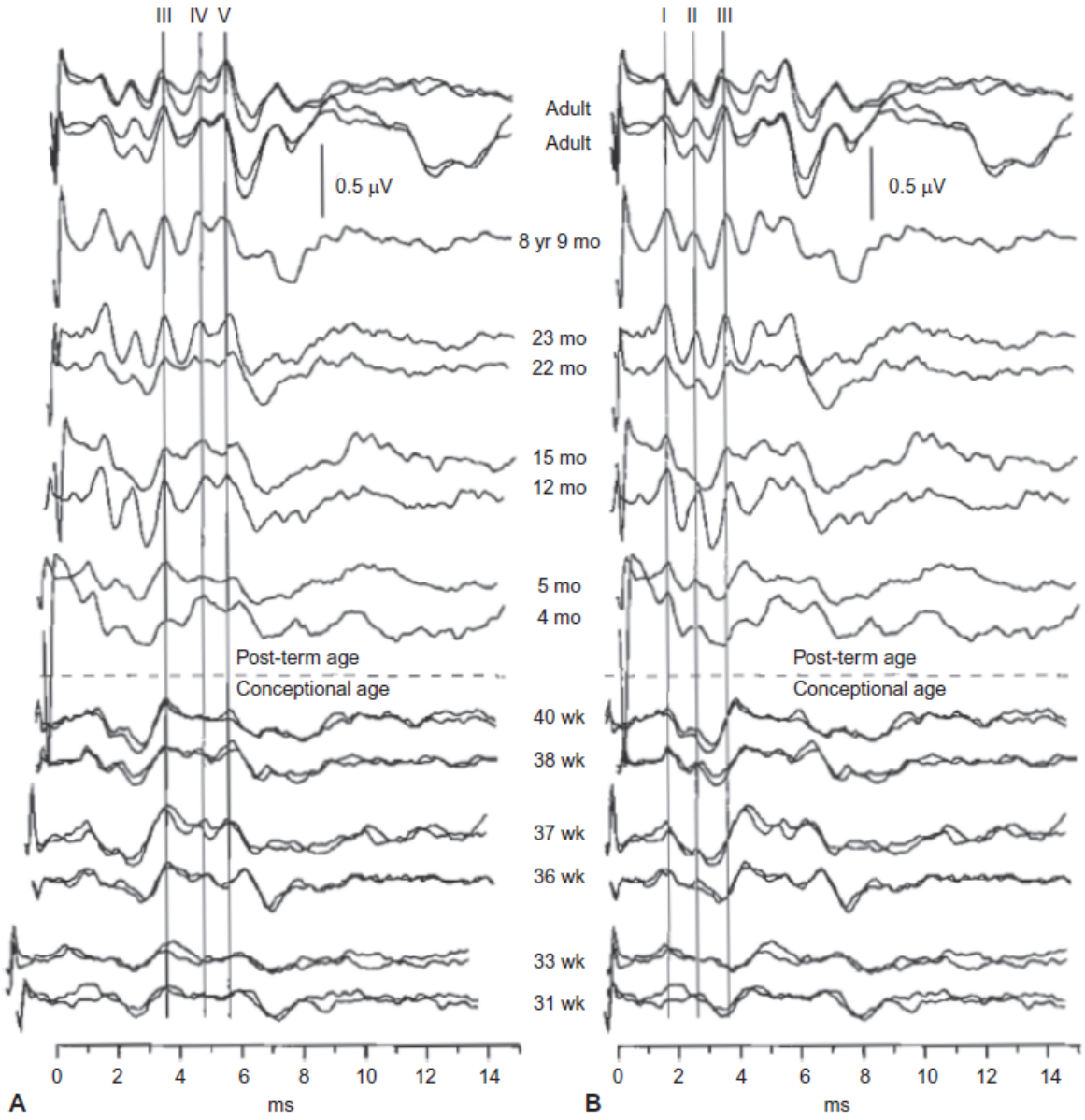


Figure 3. BAER are shown for preterm infants, older infants, children, and adults. Overlaid traces represent repeated recordings from a single subject. Age is expressed as conceptional age in weeks (wk CA) for preterm infants, and as post-term age in months (mo) or years (yr) for older infants and children.
(A) Unmasked BAERs are aligned across subjects using wave III as the reference point. Adult peak latencies for waves III, IV, and V are indicated by vertical markers. Wave IV demonstrates minimal latency change up to 36–40 wk CA, whereas wave V remains delayed even in more mature infants. **(B)** The same recordings are shown with alignment based on wave I. Vertical markers indicate adult peak latencies for waves I, II, and III. Wave II does not show evident latency prolongation down to 36–37 wk CA; however, wave III exhibits clear delay postnatally. Adapted from [4].

2.2 Methodology

To elicit BAER, several recording and physiological parameters must be considered, which are described in table 2.[1] BAER is time-locked to an auditory stimulus, usually delivered by headphones or tubal insert phones, as shown in figure 4.[1] The supplies and auditory stimulators required for testing are shown in table 3. To ensure diagnostic accuracy and proper identification of peaks, a multi-derivation montage is utilized.[9] The primary derivations include:

1. Ipsilateral Derivation (Cz–Ai): This derivation is used to record all five major BAER peaks (Waves I–V).[1]
2. Contralateral Derivation (Cz–Ac): In this derivation, Wave I is typically absent because it is a near-field potential, while Waves II–V (far-field potentials) remain visible.[1]
3. Ear-to-Ear Derivation (Ac–Ai): This specific derivation is used primarily to confirm the presence and identity of Wave I, as other peaks are less clearly defined in this setup.[1]

Figure 5 shows a visual representation of the relevant anatomical landmarks (such as Cz, Fz, A1, and A2) which can be found in the International 10/20 EEG electrode positioning system diagram.[3] Currently, there are no international guidelines or standardization on the recording parameters for neonatal and pediatric patients. Table 4 summaries the parameters used by the other laboratories, one may consider using similar parameters and recording techniques.

Table 2. An overview of stimulation, recording and physiological parameters and their clinical impacts on BAER. Adapted from Husain, A. M. (2018). *Illustrated Manual of Clinical Evoked Potentials* (pp. 114 - 128).

Category	Description	Clinical Impact
Stimulus Type (Broadband Clicks) See Appendix A	100-µs sound pulses containing a wide range of frequencies with a rapid rise and fall in intensity.	The standard for neurologic assessments; these clicks stimulate a large section of the cochlea to generate robust brainstem signals.
Stimulus Type (Tone Pips/Filtered Clicks) See Appendix A	Sound stimuli restricted to specific frequency ranges.	Primarily utilized for audiologic testing to evaluate the functional integrity of specific regions of the cochlea.
Stimulus Type (Tone Bursts) See Appendix A	Acoustic stimuli characterized by a slower rise and fall of sound intensity.	Not used for standard BAEPs; these are reserved for recording middle- and long-latency auditory evoked potentials.
Sound Polarity (Rarefaction)	The acoustic click begins with the transducer diaphragm moves away from the tympanic membrane (eardrum). This action creates a negative pressure wave as the first component of the stimulus.	This is the standard starting point because it typically produces the shortest response times and the most well-defined wave shapes.
Sound Polarity (Condensation)	The acoustic click begins with the transducer diaphragm that moves towards the eardrum. This action creates an initial positive pressure wave.	Used as a backup or comparison; some specific patients may produce clearer wave definitions with this polarity even if latency is slightly delayed.

Sound Polarity (Alternating)	The software changes between rarefaction and condensation pulses for every other click delivered.	Essential for high-volume testing; it neutralizes electrical interference (stimulus artifact) that would otherwise hide the earliest brain response peaks.
Stimulation Volume (Intensity)	The loudness of the click pulses, expressed in decibels above the average human hearing threshold (often measured in dB nHL). See Appendix B for details.	Increasing volume generally improves wave amplitude and morphology, which is vital for identifying peaks in patients with hearing loss or noisy recordings.
Click Rate (Repetition)	The speed at which click stimuli are delivered, with 11.1 per second being the standard slow rate.	While standard rates are easiest to record, using fast rates (e.g., 51.1/s) can stress the auditory pathway to reveal neurological deficits that slow rates might miss.
Background Masking Noise	A steady stream of white noise played into the ear that is not currently being tested.	This prevents "cross-hearing," ensuring that the recorded brain signal is specifically generated by the auditory nerve on the side intended for the test.
Multi-Channel Montages	The specific combination of sensors at the head (Cz) and earlobes (Ai/Ac) used for recording.	Comparing same-side and opposite-side channels is necessary to confirm peak identities, as some waves only appear on the stimulated side.
Filter Bandpass Settings	Electronic limits (typically 10–3,000 Hz) used to block unwanted electrical noise from body movements.	Raising the low-frequency limit to 150 Hz helps flatten a drifting baseline, making it significantly easier to measure peak arrival times accurately.
Trial Averaging	The acquisition system averages 1,000 to 4,000 individual responses to create a single readable wave.	This is necessary to extract the extremely faint brain signal from the massive background noise of regular muscle and brain activity.
Interpeak Latencies (IPL)	The measurement of the time intervals between major waves (I–III, III–V, and I–V).	The primary diagnostic marker; these intervals measure conduction speed through the brainstem, helping to localize specific neurological lesions.
Amplitude Ratios (V/I Ratio)	A comparison of the height of Wave V relative to the height of Wave I.	A ratio below 0.7 (adult) can suggest pathology, providing a secondary indicator of brainstem health alongside timing measurements.
Patient Muscle State	The level of physical activity and tension in the patient's neck and jaw during the procedure.	Excessive tension creates "muscle noise" that can bury the brain's signals; testing

		during natural sleep or relaxation is ideal for accuracy.
Patient Maturation (Age)	The developmental status of the patient's central nervous system.	Newborns have naturally slower responses that shorten as they age; clinicians must use age-specific standards to avoid misdiagnosis.
Biological Sex	The gender of the patient at birth.	Because women typically have faster conduction times than men, gender-specific normal values are used to ensure the most accurate interpretation.

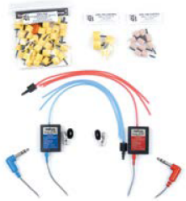
Figure 4. Different types of auditory stimulation devices: Shielded headphones (left), unshielded headphones (center) and insert tubal phones (right).

Table 3. An overview of the supplies and auditory stimulators required for performing BAER, part numbers from Natus Supply Catalog.

Part Number	Description	Compatibility
842-202700	Unshielded Headphones, 300 Ohm	Nicolet VikingQuest or EDX system with auditory stimulator
842-202300	Shielded Headphones, 300 Ohm	

Part Number	Description	Compatibility
9031E0258	Calibrated Headphones	Natus UltraPro S100, Dantec Keypoint Focus & Keypoint G4 with auditory stimulator

Part Number	Description	Connector	Quantity	Compatibility
041-704000	TIP 300 Kit	Dual phone plugs (full size)	1 kit/pkg	Nicolet systems



Part Number	Description	Connector	Quantity	Compatibility
9031E0277	Dantec Keypoint TIPs Kit	9-pin DIN	1 kit/pkg	Dantec Keypoint G4, Keypoint Focus & Natus UltraPro S100 EMG systems

Part Number	Type	Quantity	Compatibility
1700-9604	13mm, yellow	50/pkg	All Natus Tubal Insert Phones
1700-9605	10mm, beige	50/pkg	

Part Number	Cup Type	Wire Length & Type	Connector Type	Quantity
F-E5GH-12	10mm Gold with 2mm hole	12" (0.31m) Lightweight Teflon	Molded 1.5mm touchproof	10/box
F-E5GH-24	10mm Gold with 2mm hole	24" (0.61m) Lightweight Teflon	Molded 1.5mm touchproof	10/box
F-E5GH-30	10mm Gold with 2mm hole	30" (0.76m) Lightweight Teflon	Molded 1.5mm touchproof	10/box
F-E5GH-48	10mm Gold with 2mm hole	48" (1.22m) Lightweight Teflon	Molded 1.5mm touchproof	10/box
F-E5GH-60	10mm Gold with 2mm hole	60" (1.52m) Lightweight Teflon	Molded 1.5mm touchproof	10/box
F-E5GH-72	10mm Gold with 2mm hole	72" (1.83m) Lightweight Teflon	Molded 1.5mm touchproof	10/box
F-E5GH-96	10mm Gold with 2mm hole	96" (2.44m) Lightweight Teflon	Molded 1.5mm touchproof	10/box
F-E5GH-120	10mm Gold with 2mm hole	120" (3.05m) Lightweight Teflon	Molded 1.5mm touchproof	10/box
F-E6GH-48	6mm Gold Ped with 1.5mm hole	48" (1.22m) Lightweight Teflon	Molded 1.5mm touchproof	10/box

Part Number	Type	Size	Quantity
026525	Ten20 Conductive Paste	Single-Use Cups 0.5oz (15g)	24/pkg
1411003	Ten20 Conductive Paste	4oz (114g) jar	3/pkg
016-703700	Ten20 Conductive Paste	8oz (228g) jar	3/pkg
122-736000	Ten20 Conductive Paste	4oz (114g) tube	3/pkg

Part Number	Type	Size	Quantity
024065	NuPrep Skin Prep	1oz (25g) tube	6/pkg
122-736100	NuPrep Skin Prep	4oz (114g) tube	3/pkg
042679	NuPrep Single Patient Cups	0.32oz (9G) Cups	24/pkg

Part Number	Type	Width	Length	Quantity
101917	3M Transpore Surgical Tape	1" (2.5cm)	30' (9m) roll	12/pkg

Part Number	Type	Quantity
101432XL	Retractable, inches & centimeters, vinyl tape for surface & other measurements	1/pkg
EDAID2	International 10-20 Electrode Placement, 0-70 one side; 35-0-35 on the other, Tyvek® tape	2/pkg

Part Number	Type	Color	Quantity
EM1	Sharpie® Peel-Off™ China Marker	Red	12/pkg
EM2	Sharpie® Peel-Off™ China Marker	White	12/pkg
EM3	Sharpie® Peel-Off™ China Marker	Blue	12/pkg
270-401000	Wet Erase Marker	Blue	1/pkg

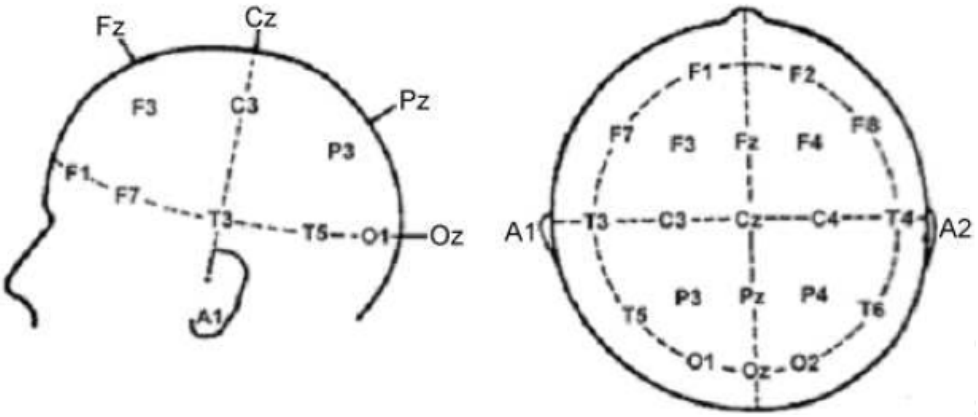


Figure 5. International 10/20 EEG electrode positioning system diagram. Adapted from Akay, A. (2012). Evoked Potentials. InTech. doi: 10.5772/33368

Table 4. Summary of key recording techniques and parameters for BAER. Adapted from various sources. [1, 3, 12, 13, 14, 15, 16, 17, 18]

Category	Parameter	Description
Acoustic Stimulation	**Stimulus Type**	Monaural broadband clicks of ~100 µs duration are used for standard assessments.
	Transducers	Insert earphones preferred in infants to avoid ear canal collapse from heavier supra-aural headphones.
	Intensity	Clinical neurologic tests: 60–90 dB nHL. Newborn screening: 25–35 dB nHL for detecting mild hearing loss.
	Polarity	Rarefaction clicks used initially for shortest latencies and clearer waveforms. Alternating polarity is used at high intensities to reduce stimulus artifact.
	Click Rate	Routine: 10–21.1/s. Faster rates (51.1–91/s) or Maximum Length Sequence (up to 1000/s) used to stress auditory pathway and reveal subtle neuropathology.
	Masking	White noise (30–55 dB nHL) applied to non-test ear to prevent cross-hearing and ensure monaural recording.
Recording & Signal Processing	**Amplification & Filtering**	Signals (~0.25 µV) require ~500,000× amplification. Bandpass filters: typically, 100–3000 Hz; high-pass may be raised to 150 Hz to reduce muscle artifacts.
	Impedance	Interelectrode impedances should be maintained below 5 kΩ to ensure clear signal acquisition.
	Analysis Window (Sweep)	Neonates/children: 15–20 ms due to prolonged latencies.
	Averaging	1,000–4,000 trials averaged per run to isolate responses from noise. Each recording should be replicated at least twice for reliability.

Patient Considerations	**Behavioral State**	Testing is ideally performed during natural sleep (often post-feeding) to minimize movement and muscle artifacts.
	Sedation	If natural sleep is not achievable and muscle noise is excessive, conscious sedation (e.g., chloral hydrate or trichlorophos) may be used per institutional guidelines.
	Environment	Conduct testing in a quiet, sound-treated, and preferably electrically shielded room to minimize acoustic and electrical interference.

2.3 Indications

The BAER is a vital electrophysiological tool for evaluating the functional integrity of the auditory pathway and the central nervous system in neonatal and pediatric populations. As an objective measure, it is uniquely valuable in young or critically ill children because it does not require patient cooperation and is largely unaffected by the patient's level of consciousness or most sedative medications. Several indications and their utilities are described in Table 6, while figure 6-10 illustrated the abnormalities in BAER in different diseases, such as Alexander disease, hyperbilirubinemia, Krabbe disease (Globoid cell leukodystrophy, GLD), Metachromatic Leukodystrophy (MLD), perinatal asphyxia, amongst others.

Table 6. An overview of Clinical Applications of BAER/ABR in Pediatric and Neonatal Care. Adapted from various sources.[1, 10, 19, 20, 21, 22, 23, 24]

Domain	Indication	Clinical Utility
Hearing Evaluation & Screening	Universal Newborn Hearing Screening (UNHS)	Primary tool for early detection of congenital hearing loss, enabling timely intervention for speech and language development.
	Detection of Retrocochlear Pathology	Identifies auditory nerve and central pathway disorders, unlike OAE which assesses only cochlear function.
	Monitoring High-Risk Infants	Screening indicated for infants with risk factors (e.g., birth weight <1500 g, family history of deafness, craniofacial anomalies, NICU stay >5 days).
Acute Neurological Assessments	Perinatal Asphyxia & Encephalopathy	Sensitive indicator of hypoxic-ischemic brainstem injury; useful for prognosticating neurodevelopmental outcomes.
	Hyperbilirubinemia (BIND)	Detects bilirubin-induced neurotoxicity; supports monitoring and reversibility assessment following treatment.

Infections & Ototoxicity	Neurological Infections	Evaluates auditory pathway damage from meningitis and congenital infections (e.g., cytomegalovirus, rubella, toxoplasmosis).
	Ototoxic Drug Monitoring	Monitors hearing in patients exposed to ototoxic agents such as aminoglycosides and diuretics.
Developmental & Degenerative Disorders	Neural Maturation Assessment	Quantifies auditory pathway maturation in preterm and small-for-gestational-age infants.
	Degenerative/Demyelinating Diseases	Localizes and tracks brainstem involvement in disorders (e.g., Krabbe, Alexander disease, adrenoleukodystrophy).
	Genetic & Developmental Syndromes	Detects characteristic abnormalities in conditions such as Down syndrome and Cornelia de Lange syndrome.
Critical Care & Specialized Monitoring	ICU & Neurosurgical Monitoring	Assesses secondary brainstem injury due to herniation or intracranial mass effects.
	Hypoxic-ischemic encephalopathy (HIE)	Objectively assess the functional integrity of the brainstem, which is highly vulnerable to oxygen deprivation.
	Complex Clinical Cases	Monitors auditory pathway integrity in hydrocephalus, chronic lung disease, and extracorporeal membrane oxygenation (ECMO) patients.

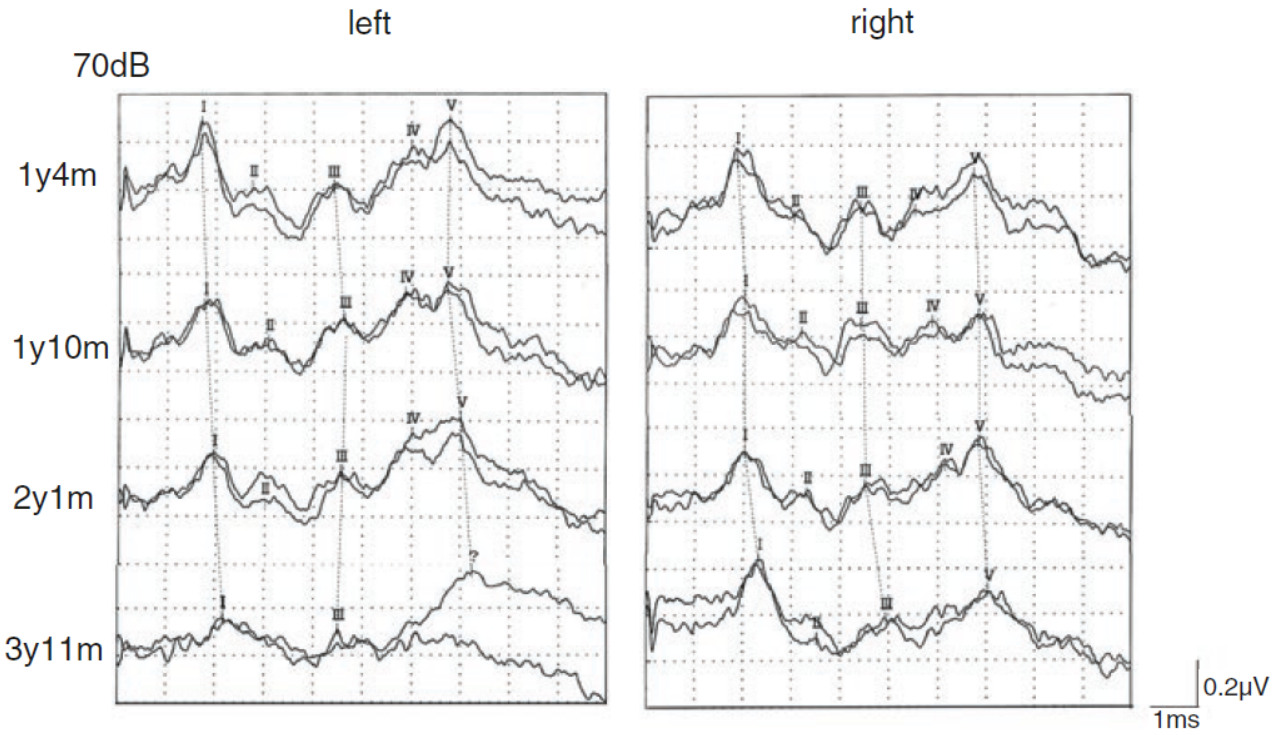


Figure 6. Serial BAER recordings from a female patient with the infantile form of Alexander disease demonstrate progressive prolongation of wave latencies and deterioration of waveform morphology over a 2-year and 7-month period. Adapted from [21].

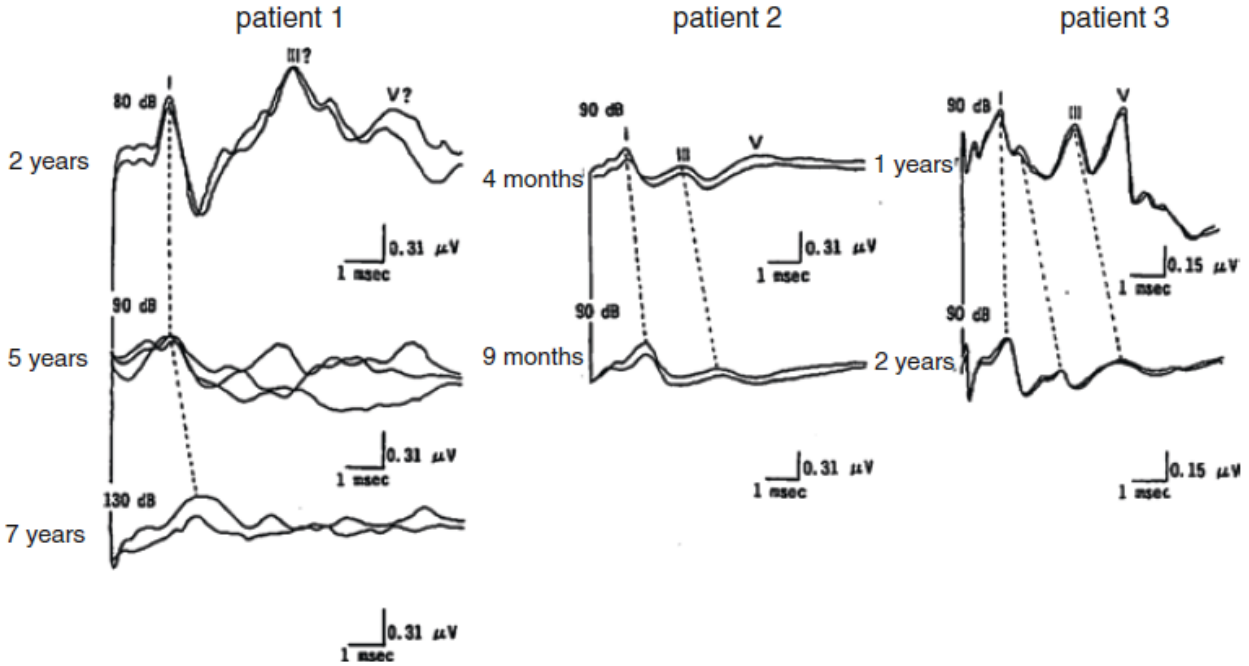


Figure 7. Serial ABR recordings from three patients with GLD demonstrate progressive changes over time, including prolonged latencies across all waves, increased interpeak intervals, and reduced amplitudes of later waves. Eventually, later waveforms became absent, with only wave I remain detectable. Adapted from [21].

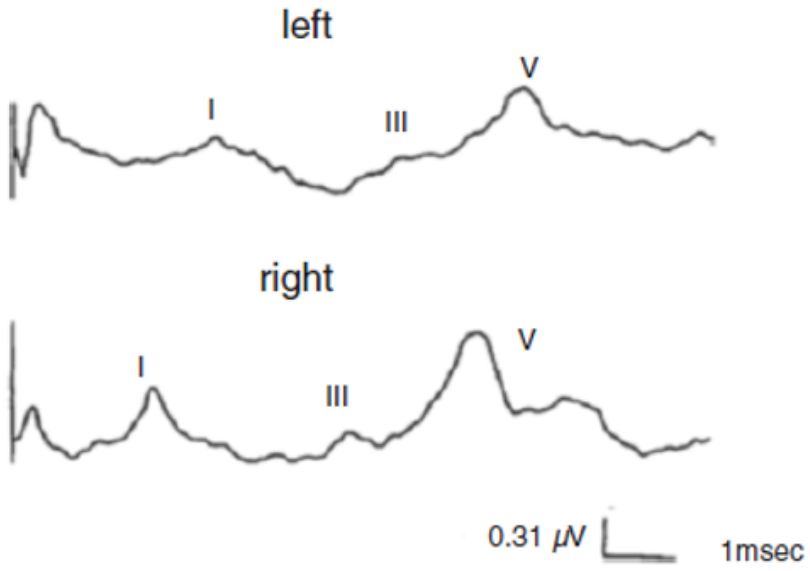


Figure 8. BAER findings in patient (17 y/o) with juvenile MLD showed prolonged latency of bilateral wave I, as well as extended I–III and I–V interpeak intervals on the right side. Clinically, symptoms began at 6 years of age with forgetfulness, followed by bladder and bowel incontinence and progressive cognitive and motor decline. The ABR pattern suggests conductive hearing involvement along with pontine pathology, evidenced by delayed bilateral wave I and prolonged I–III interpeak latencies. Adapted from [21].

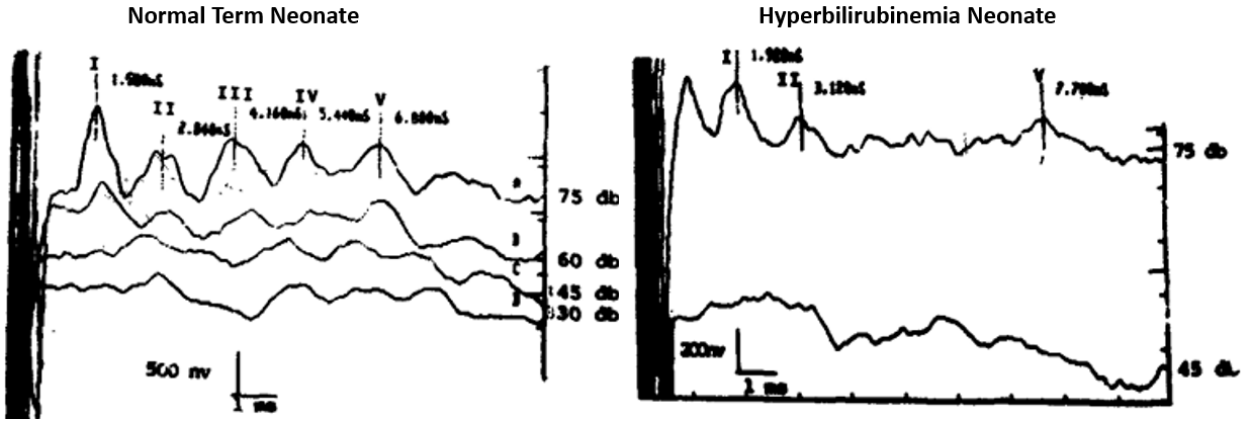


Figure 9. Left: BAER recording from a normal term neonate, with wave V detectable down to a 30 dB nHL click stimulus. Right: BAER recording from a neonate with hyperbilirubinemia (serum bilirubin 35 mg/dL), demonstrating prolonged brainstem conduction times and an elevated auditory threshold (fail at 45 dB). Adapted from [22].

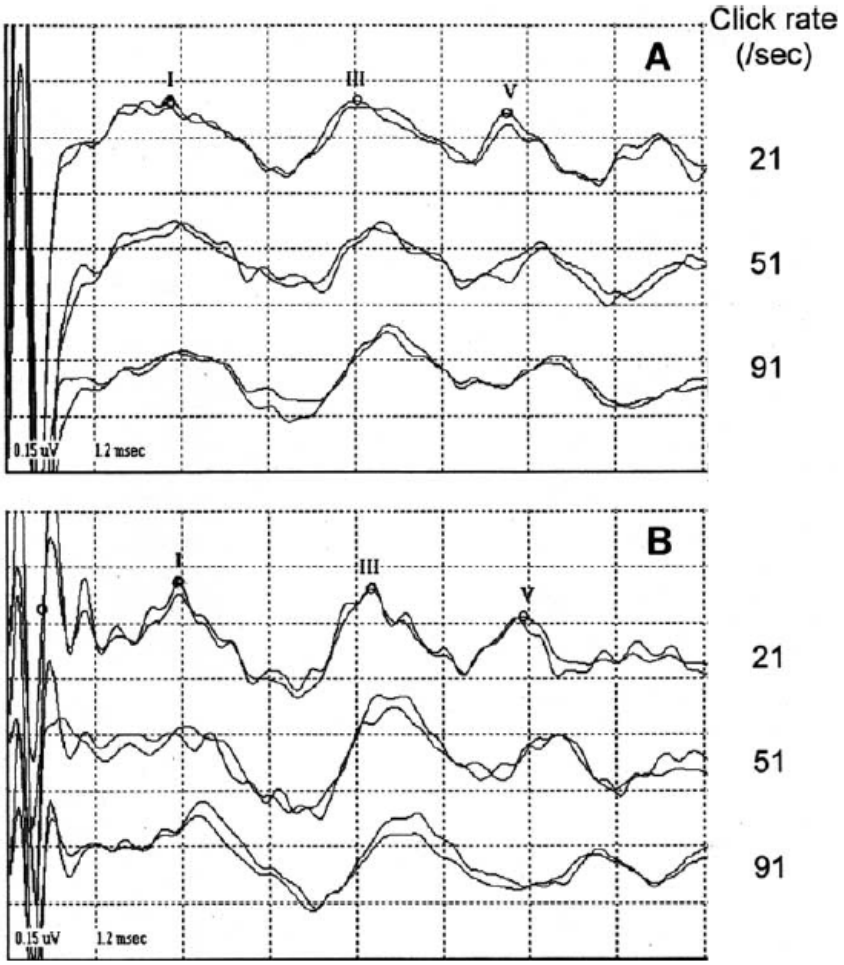


Figure 10. BAER recordings obtained on day 3 using different click rates: (A) normal infant; (B) infant with a history of perinatal asphyxia.

2.4 Interpretation

The interpretation of BAERs in neonates and pediatric patients requires a specialized approach that accounts for the rapid maturation of the central nervous system.[1, 18] Unlike adult assessments, clinicians must recognize that peak latencies are naturally prolonged in newborns due to incomplete myelination and progressively shorten until they reach adult values around age two.[10, 18] Because infant waveforms often differ from adults—such as a frequently "bifid" (double-peaked) Wave I, a diminished or absent Wave II, and a lower Wave V/I amplitude ratio—the interpretation focus remains on the most replicable components: Waves I, III, and V. [10, 18, 25] The differences can be appreciated by comparing the BAER of a term neonate (Figure 11) with that of a preterm neonate (less than 37 weeks old), as illustrated in Figure 3.

In clinical practice, interpretation begins by determining if a recording is normal or abnormal based on established age-specific normative data, ideally established within the same laboratory to ensure methodological consistency.[1,15, 25] Normative data for Brainstem Auditory Evoked

Responses (BAER) in neonates are characterized by prolonged absolute latencies and increased interpeak intervals compared to adult values, reflecting the incomplete myelination and maturation of the central nervous system at birth.[1, 18, 25] These values progressively shorten as the infant ages, typically reaching adult patterns between 18 months and 2 years of age. [1, 10, 18] Table 7 summarizes normative BAER values derived from multiple studies, including absolute wave latencies, interpeak intervals, amplitudes, and key maturational characteristics.[12, 15, 17, 27] While it serves as a useful general reference, individual laboratories are encouraged to establish their own normative datasets to ensure methodological consistency.[1,15, 25]

For universal hearing screening, a "pass" is generally defined by the presence of identifiable Waves I and V at low stimulation intensities, typically 25 to 35 dB nHL.[1, 13] Conversely, abnormalities are identified by a total lack of response, absolute wave latencies exceeding two standard deviations from the mean, or significantly prolonged interpeak latencies (IPLs).[1,18] Figure 12 demonstrates BAER threshold testing across decreasing stimulus intensities, identifying the lowest level at which wave V remains detectable.

Interpretation also involves distinguishing between peripheral and central pathologies. A peripheral pattern of abnormality is characterized by elevated thresholds or prolonged latencies for Wave I, indicating issues at the level of the acoustic nerve or middle ear. A central pattern is identified by an increased I–V interpeak interval or the absence of components following Wave I, suggesting conduction delays within the brainstem. Furthermore, a Wave V/I amplitude ratio below 0.7 may serve as a secondary diagnostic marker for brainstem health, particularly in acute conditions like perinatal asphyxia or hyperbilirubinemia. Figure 13 presents a range of BAER waveform patterns obtained under different stimulus conditions, particularly at high frequencies and elevated sound pressure levels.[13] While Table 9 describes the potential lesion according to the BAER findings.[4]
In addition, Hasani et al. (2013) examined children aged 4–6 years born at term and preterm. Their BAER findings demonstrated significant differences in the I–III and III–V interpeak intervals, as well as in the absolute latency of wave III (Table 8). They reported that preterm children showed prolonged wave latencies compared with their term counterparts. These findings suggest possible involvement of multiple regions within the central auditory brainstem, highlighting the need for ongoing monitoring to identify children who may benefit from hearing amplification and to mitigate potential educational and social challenges.[26]

Finally, because many neonatal abnormalities can be transient or reversible with treatment, serial recordings are often recommended to monitor recovery or developmental progression.[1, 19, 21]

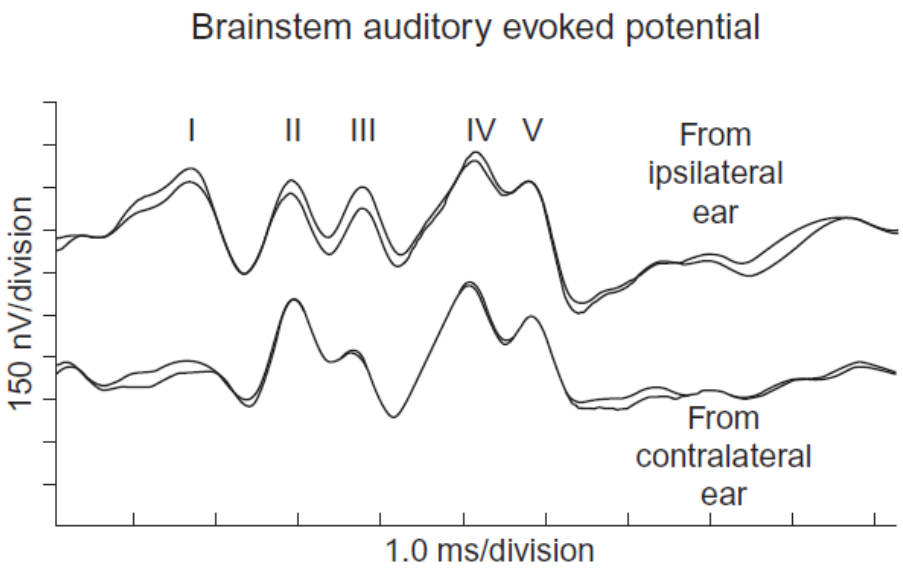


Figure 11. Illustration of typical BAER in a neonate. The sequential waves (I–V) originate from distinct anatomical sources: wave I from the eighth cranial nerve, wave II from the cochlear nucleus and vestibulocochlear nerve, wave III from the ipsilateral superior olivary complex, wave IV from the lateral lemniscus (its nuclei or fibers), and wave V from the inferior colliculus. Adapted from [13].

Table 7. Normative ranges of auditory brainstem response parameters in term and preterm neonates, including absolute wave latencies, interpeak intervals, amplitudes, and key maturational characteristics. Adapted from various sources [12, 15, 17, 27].

Parameter	Term Neonates	Preterm Neonates	Notes / Clinical Significance
Absolute Latencies			
Wave I	1.45 – 2.30 ms	Prolonged; often the only identifiable wave at ~30 weeks GA	Reflects auditory nerve function
Wave III	4.14 – 5.02 ms	Delayed; may be absent early, appears with maturation	Generated in cochlear nucleus/superior olive
Wave V	6.25 – 7.22 ms	Delayed, low amplitude	Key marker for auditory brainstem integrity
Interpeak Latencies (IPL)			
I–III Interval	2.15 – 2.81 ms	Prolonged	Indicates conduction from auditory nerve to lower brainstem
III–V Interval	2.01 – 2.19 ms	Prolonged	Reflects upper brainstem conduction

I–V Interval (Central Conduction Time)	~4.91 – 5.22 ms (upper limit ~5.8 ms)	Prolonged	Primary diagnostic indicator of brainstem maturation
Thresholds and Amplitudes			
Hearing Threshold	25 – 35 dB nHL	Elevated thresholds common	Screening pass often at 35 dB with Waves I and V present
Wave V/I Amplitude Ratio	>0.7	Often reduced	Lower ratios may indicate pathology
Mean Amplitude (60 dB)	Wave I: ~0.179 µV Wave III: ~0.218 µV Wave V: ~0.208 µV	Reduced amplitudes	Reflects neural synchrony
Maturational Characteristics			
Wave Morphology	Distinct waves	Less defined, fused waveforms	Reflects incomplete myelination
Wave I	May appear bifid	Prominent early	Double peak common in neonates
Wave II	Often small or absent	Frequently absent	Immature generator function
Waves III–V	Clearly separated	Often fused complex	Separate with maturation
Developmental Trend	Stable	Rapid latency reduction toward term	Fastest changes before ~34 weeks GA

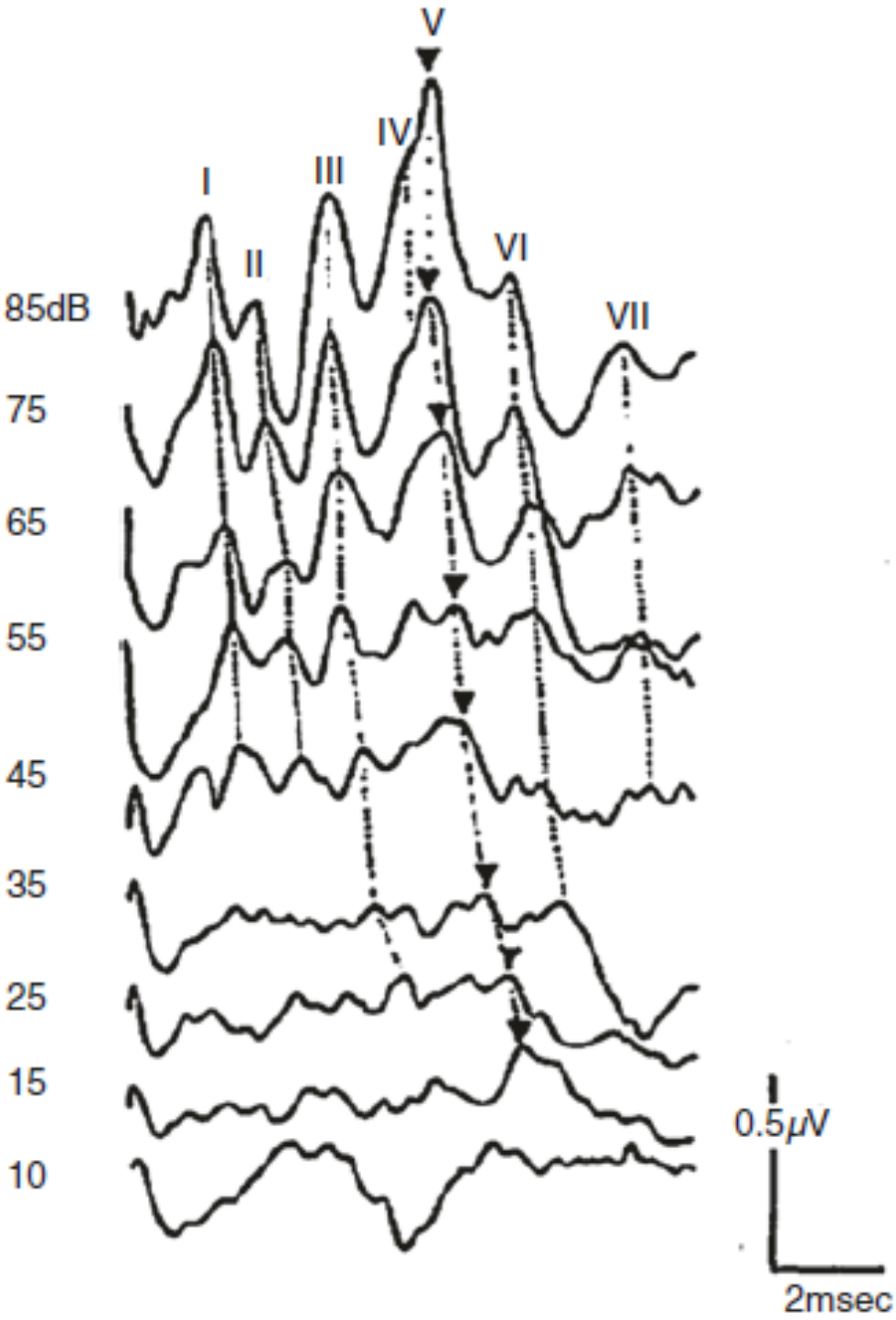


Figure 12. In a normal BAER, high-intensity click stimuli produce well-defined waveforms (I–VII). As stimulus intensity decreases, wave amplitudes diminish and latencies become progressively prolonged. The lowest intensity at which wave V can still be clearly identified closely approximates the hearing threshold for high-frequency sounds. Adapted from [13].

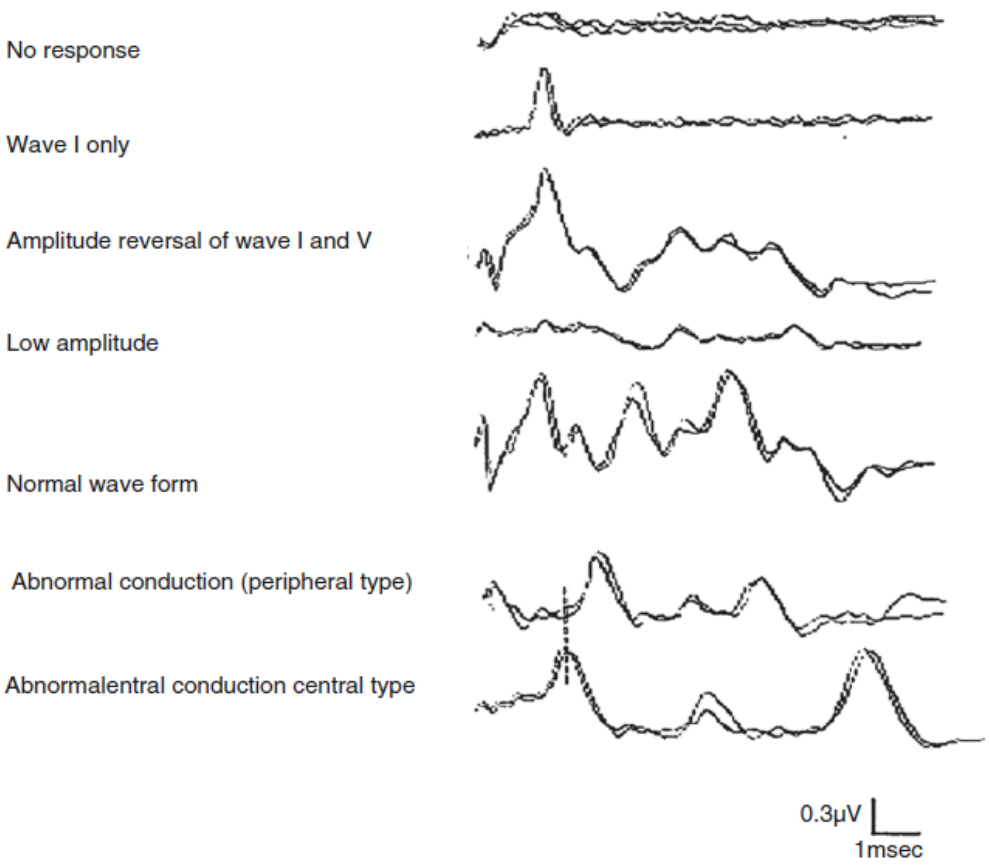


Figure 13. Illustration of various BAER waveforms with varying stimuli configurations, especially at high frequencies and sound pressure level. Absence of responses may indicate profound hearing loss or severe brainstem dysfunction, while the presence of wave I alone suggests significant post–auditory nerve pathology. Amplitude reversal between waves I and V is nonspecific, though wave V is typically larger. Reduced amplitudes may reflect elevated hearing thresholds or diffuse brainstem involvement. Prolonged interpeak latencies indicate abnormal conduction, and a delayed wave I with normal subsequent intervals is consistent with conductive hearing loss. Adapted from [13].

Table 8. Comparison of absolute latencies and interpeak intervals of ABR waves in term and preterm children aged 4 to 6. Adapted from [26].

ABR waves (ms)	Premature children		Normal children		P-value
	Mean	SD	Mean	SD	
Inter-peak latency of I–III	2.20	0.11	2.07	0.20	0.00
Inter-peak latency of III–V	1.84	0.13	1.92	0.12	0.002
Inter-peak latency of I–V	4.00	0.32	3.99	0.23	0.793
Absolute latency of I wave	1.36	0.10	1.41	0.15	0.055
Absolute latency of III wave	3.57	0.17	3.49	0.19	0.019
Absolute latency of V wave	5.36	0.36	5.41	0.23	0.348

Table 9 . Overall Abnormal Patterns of BAER. Adapted from *Clinical neurophysiology* (3rd ed) (p.480), by Daube, J. R., & Rubin, D. I. (2009).

Brainstem auditory evoked potential finding	*Lesion*
Prolonged wave I latency	Distal CN VIII
Prolonged I–III interpeak latency	Between proximal CN VIII and pons (CPA masses)
Prolonged III–V interpeak latency	Lesion between caudal pons and midbrain (stroke, tumor, MS, ICH, AVM, etc.)
Prolonged I–III and III–V latencies	Both rostral pons or midbrain and acoustic nerve or caudal pons
Absent wave I with normal III and V	Mild to moderate peripheral hearing loss
Absent wave III with normal I and V	Normal variant
Absent wave V with normal I and III	Above the caudal pons
Absence of all waves	Severe hearing loss
Absence of all waves except I (and possibly II)	Brain death

[a]CN, cranial nerve; CPA, cerebellopontine angle; MS, multiple sclerosis; ICH, intracranial hemorrhage; AVM, arteriovenous malformation.

3. Pitfalls

3.1 Technical and Methodological Pitfalls

A potential technical risk in testing premature infants is external ear canal collapse caused by the weight and pressure of standard supra-aural headphones, which can result in inaccurate findings that falsely suggest hearing loss.[1, 28] To avoid this, clinicians often use tubal insert phones or hold standard headphones slightly away from the ear. [1, 25] The neonatal intensive care unit (NICU) environment itself is often "hostile" for clear recordings due to high levels of background noise and electrical interference from life-support equipment, despite using averaging techniques.[29, 30] While alternating polarity can neutralize or reduce these environmental, electrical or stimulus artifacts, it may also lead to lower wave amplitudes because the individual responses to different polarities (rarefaction and condensation) can have slightly different timings (figure 14).[1] Additionally, the Common-Mode Rejection Ratio (CMRR) is a critical technical specification for recording because it determines an amplifier's ability to suppress noise while preserving weak biological signals.[35] For instance, Mucci (2024) highlighted that an amplifier with a CMRR of 106 dB is twice as efficient at suppressing noise as one with 100 dB. Thus, one should consider using the EMG system with a high CMRR amplifier (table 10). Readers are encouraged to review the technical note on CMRR written by Mucci (2024) in detail.

Moreover, incorrect filter settings can distort waveforms; for instance, high-pass filters may cause phase advances that make waves appear earlier, while raising the low-frequency limit can eliminate later responses entirely (figure 15).[14, 31] At very high click repetition rates (e.g., >

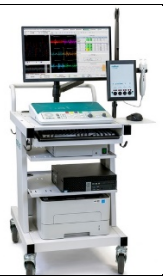
51/second), stimulus artifacts can overlap with and obscure the latter part of Wave V (figure 16), making it difficult to obtain a reliable measurement.[10]

Table 10. An overview of EMG amplifiers for Natus EMG system UltraPro S100, Keypoint Focus and Keypoint G4.

Part Number	EMG Amplifiers
9033UP731	UltraPro S100 3 Channel Amplifier
9031UP742	UltraPro S100 4 Channel Amplifier

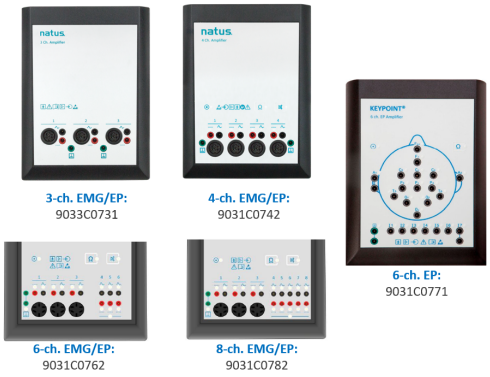
Compatibility: UltraPro S100
CMRR: >124 dB

Part Number	EMG Configurations
982A0596	UltraPro S100 International



Part Number	EMG / EP Amplifiers
9031C0732	3-ch. EMG/EP Amplifier
9031C0742	Natus 4 channel Amplifier
9031C0762	6-ch. EMG/EP Amplifier
9031C0771	6-ch. EP Amplifier
9031C0782	8-ch. EMG/EP Amplifier

Compatibility: Keypoint Focus and G4
CMRR: >124 dB



Part Number	EMG / EP Configurations
9033A07-SYS-CN	NATUS KEYPOINT FOCUS MODULE KIT FOR CHINA
9033A07-SYS	NATUS KEYPOINT FOCUS MODULE KIT
9033A07D-EN115	NATUS KEYPOINT FOCUS DESKTOP SYSTEM, ENG, 115V
9033A07D-EN230	NATUS KEYPOINT FOCUS DESKTOP SYSTEM, ENG, 230V
9033A07D-FRE	NATUS KEYPOINT FOCUS DESKTOP SYSTEM, FRE
9033A07D-GER	NATUS KEYPOINT FOCUS DESKTOP SYSTEM, GER
9033A07D-ITA	NATUS KEYPOINT FOCUS DESKTOP SYSTEM, ITA

Keypoint Focus

Part Number	EMG / EP Configurations
9031A07D-CN	NATUS KEYPOINT G4 DESKTOP SYSTEM, CN
9031A07D-EN115	NATUS KEYPOINT G4 DESKTOP SYSTEM, ENG, 115V
9031A07D-EN230	NATUS KEYPOINT G4 DESKTOP SYSTEM, ENG, 230V
9031A07D-FRE	NATUS KEYPOINT G4 DESKTOP SYSTEM, FRE
9031A07D-GER	NATUS KEYPOINT G4 DESKTOP SYSTEM, GER
9031A07D-ITA	NATUS KEYPOINT G4 DESKTOP SYSTEM, ITA

Keypoint G4

3.2 Interpretive Pitfalls

Interpretive errors are frequently tied to the rapid maturation of the central nervous system, meaning that "normal" values change on a weekly basis.[14, 18] Using adult benchmarks or incorrect gestational age standards can lead to a misdiagnosis of neurological impairment. [1, 14, 18, 25] Identifying specific peaks is also challenging because neonatal waveforms differ from adult patterns: Wave I is often naturally bifid (double-peaked), Wave II is frequently diminished or absent, and later waves (III, IV, and V) are often fused into a single complex.[14] While a Wave V/I amplitude ratio below 0.7 in adults is often a sign of pathology, this ratio is naturally lower in healthy neonates, making it a less reliable standalone marker in this population.[1, 18] Interpretation requires careful differentiation between peripheral disorders (middle/inner ear) and central disorders (brainstem).[18] While Wave I is typically spared in central lesions, a peripheral issue will prolong all subsequent waves, potentially masking a concurrent brainstem problem.[20] Furthermore, automated labeling algorithms used by modern equipment may often fail when responses are abnormal, necessitating manual verification by an experienced clinician.[14]

3.3 Clinical and Patient Pitfalls

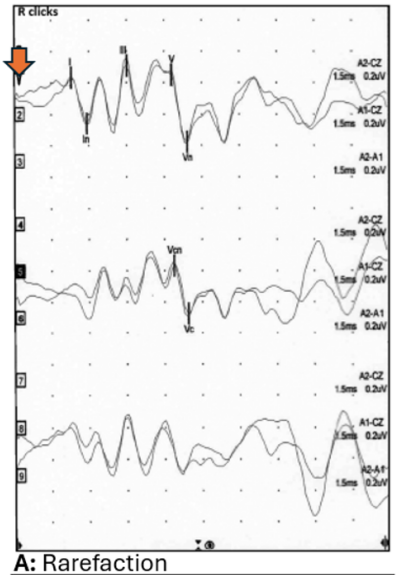
From a clinical standpoint, newborn hearing screenings have a notable rate of false positives; approximately 20% of infants may "fail" at birth due to transient issues like fluid in the middle ear, though only a small fraction have true permanent hearing loss when re-tested months later.[1, 14] While BAER is a standard tool, it is not always a reliable predictor of long-term audiological or neurological outcomes when recorded during the early premature period. [13, 25] Results are more dependable when infants are closer to term or before three months of corrected age. [13, 25] One may consider serial BAER recording to distinguish between transient and permanent injuries, and detect late-onset hearing loss that may not be apparent at birth.[14, 21]

Moreover, clinicians should be wary of overdiagnosis and underdiagnosis risks. Failure to recognize that BAER abnormalities can stem from various acquired or congenital brainstem issues rather than just primary hearing loss can lead to incorrect clinical predictions. [18] Conversely, a normal BAER does not completely guarantee a normal neurological outcome, especially in cases of severe brain injury.[32]

Confounding medical variables, such as hyperbilirubinemia, neonatal meningitis or the use of ototoxic medications (e.g., aminoglycosides or diuretics), must be carefully ruled out before attributing BAER abnormalities to a primary brain injury. [14, 18, 20] Some abnormalities recorded during acute illness, such as those caused by high bilirubin levels, can be reversible with timely treatment like exchange transfusions (figure 17).[15, 17] This "pseudo-normalization" requires clinicians to use serial recordings rather than a single test to assess long-term prognosis.[21]

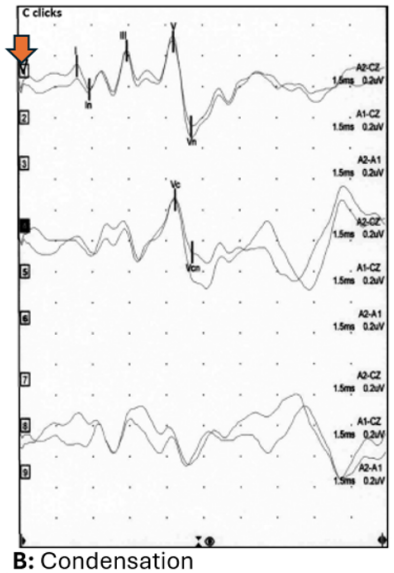
Additionally, while BAER is generally resistant to changes in consciousness or most sedatives, excessive muscle tension from a crying or distressed infant can create "noise" that buries the faint brain signals.[1, 18] Lastly, physiological factors like head size can influence conduction times,

particularly in infants with restricted growth (small-for-gestational age).[12] In small-for-gestational-age infants, a smaller head circumference can result in shorter interpeak latencies simply because the physical neural pathway is shorter.[12] This can lead to false-negative results where a maturation delay is hidden by the physically smaller brainstem.[12, 25]



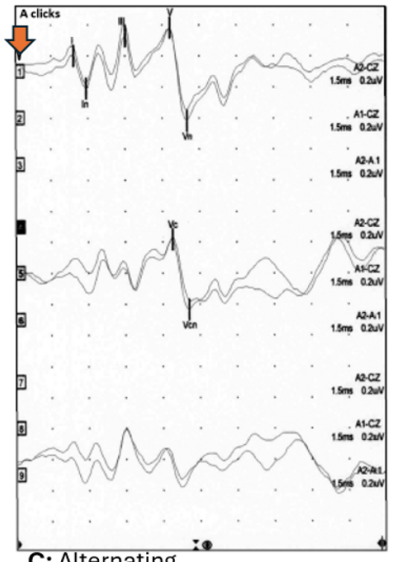
A: Rarefaction

Absolute Latencies		
Waveform	Latency (ms)	Amplitude (µV)
I	2.28	0.30 (I–In)
III	4.50	
V	6.27	0.43 (V–Vn)
Vc	6.37	
		1.41 (V/I ratio)



B: Condensation

Absolute Latencies		
Waveform	Latency (ms)	Amplitude (µV)
I	2.36	0.16 (I–In)
III	4.40	
V	6.30	0.56 (V–Vn)
Vc	6.36	
		3.43 (V/I ratio)



C: Alternating

Absolute Latencies		
Waveform	Latency (ms)	Amplitude (µV)
I	2.40	0.21 (I–In)
III	4.50	
V	6.30	0.61 (V–Vn)
Vc	6.40	
		2.86 (V/I ratio)

Montage: Cz–Ai, Cz–Ac, Ac–Ai
Stimulation rate: 11.1/s
Filters: 150–3,000 Hz
Scale: Amplitude = 0.2 µV/div;
Latency = 1.5 ms/div
Ear inserts (add 0.9 ms): Yes
Side: Right
Stimulation intensity: 70 dBnHL
Masking intensity: 40 dBnHL
Number of repetitions: 2,000

Figure 14. Effects of rarefaction, condensation, and alternating clicks in a female adult. In this example, the waveform montage is inverted; the correct montage is shown above. BAERs can be elicited using broadband clicks of either rarefaction or condensation polarity. Although both types of clicks produce similar waveforms, differences may be observed in waveform shape and latency. Rarefaction clicks (A) often result in slightly shorter latencies, and the stimulus artifact shows an upward deflection (arrow). Condensation clicks (B) may produce slightly longer absolute latencies; the stimulus artifact deflects downward (arrow). Alternating clicks (C) are created by switching between rarefaction and condensation stimuli. These can also be generated by electronically averaging responses from both polarities. Because waveform latencies differ slightly between the two, averaging may reduce waveform amplitudes. In this example, the reduction is minimal since latency differences are small. Importantly, alternating clicks eliminate the stimulus artifact (arrow) and are particularly useful at high stimulus intensities, where artifact interference can be significant. Modified and adapted from [1].

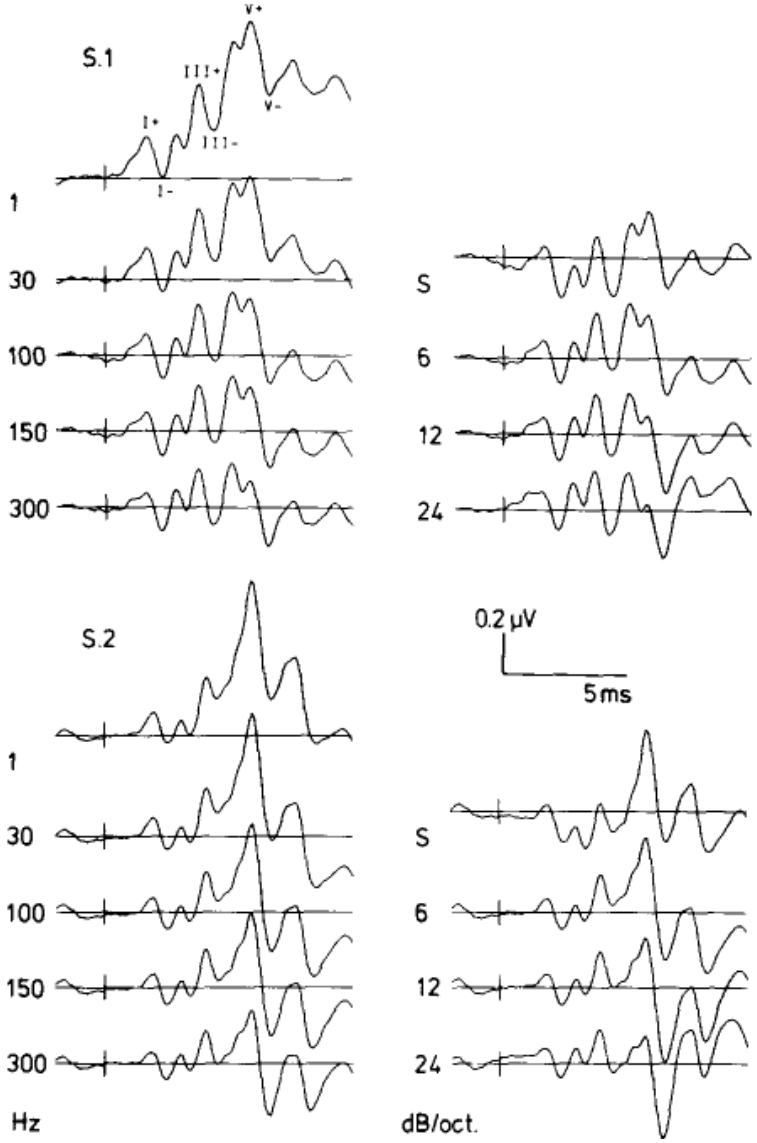


Figure 15. BAER recordings for two subjects (S1 and S2) were generated after digitally simulating filter characteristics—frequency on the left and filter slope on the right. Trace '1' represents the original wideband recording, while trace 'S' denotes the signal processed using a zero-phase shift filter. Adapted from [31].

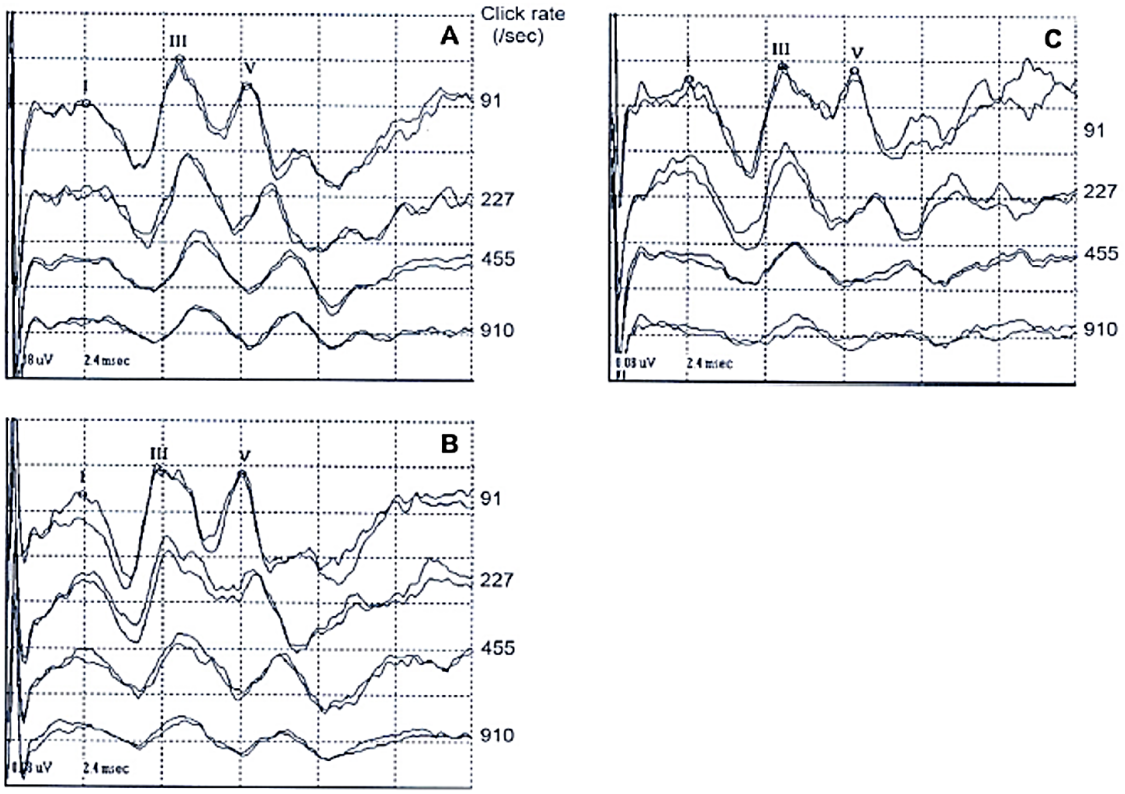


Figure 16. Maximum length sequence BAER recordings were obtained at term from three groups: a healthy full-term infant (A), a low-risk preterm infant (B), and a high-risk preterm infant (C). Comparison among these infants demonstrates a marked prolongation of wave V latency, as well as increased I–V and especially III–V interpeak intervals. There is also a notable decrease in wave V amplitude at stimulation rates of 455/s and 910/s, whereas responses at lower stimulus rates remain unaffected. Adapted from [10].

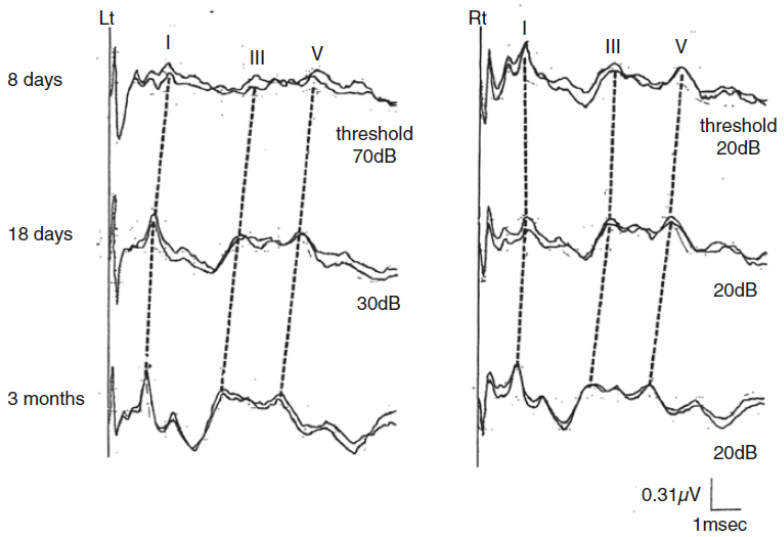


Figure 17a. Serial auditory brainstem responses (ABRs) were obtained in a neonate with jaundice. The patient was a male infant delivered at 37 weeks' gestation with a birth weight of 2450 g. At 5 days of age, peak total bilirubin and unbound bilirubin levels were 24.1 mg/dL and 1.26 mg/dL, respectively. Adapted from [21].

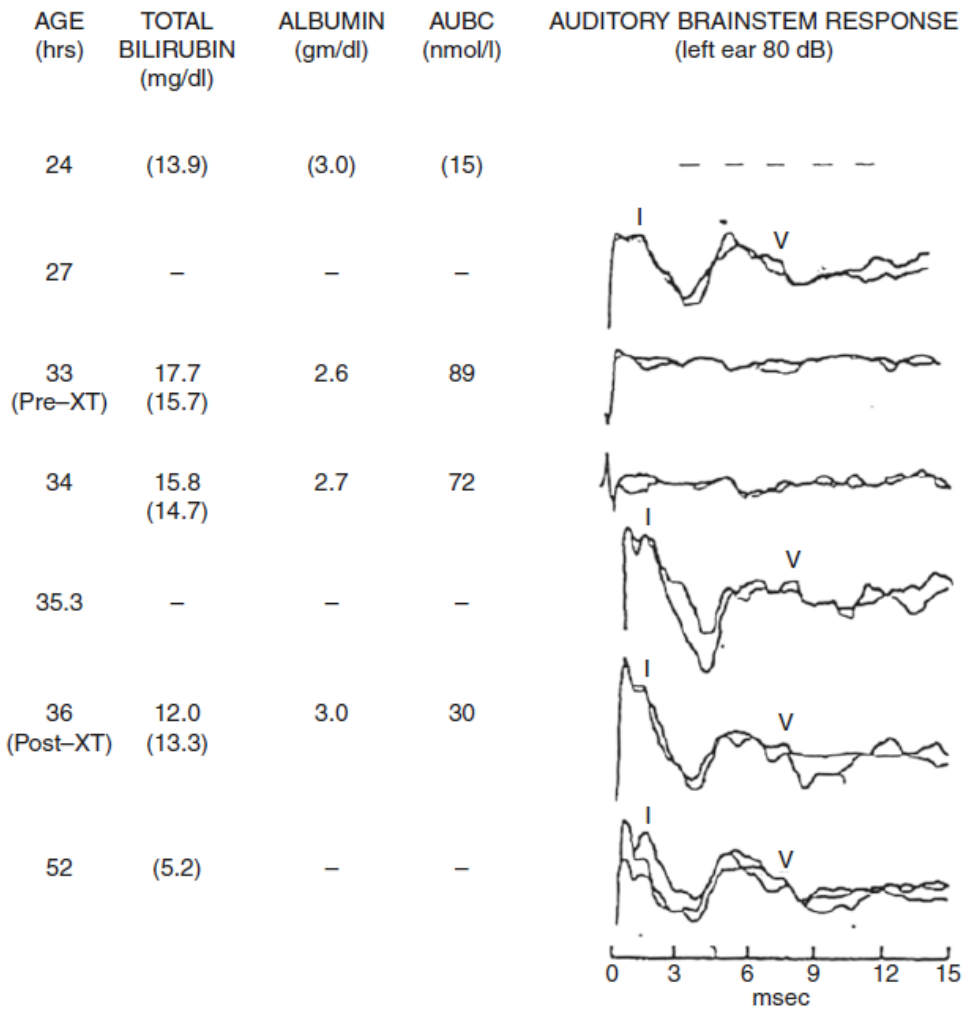


Figure 17b. Serial BAERs of a jaundice neonate with BAER recovery. Adapted from [21].

4. Discussion

BAER serves as a vital, non-invasive, and objective diagnostic tool for evaluating neurological and sensory integrity in neonates and children.[18] However, the recording environment is often suboptimal, with frequent exposure to interference and background noise. Under such conditions, the use of advanced software features, including single-point F-ratio (Fsp) and residual noise estimation (RNE), should be considered to enhance the quality of EP recordings. The Natus Elite EMG software incorporates these quantitative measures, and Mulot (2023) highlighted that such approaches can replace subjective visual interpretation with statistically robust analysis. Fsp determines if a true physiological response has been successfully extracted from the background noise, reaching an Fsp value of 3.1 provides 99% confidence that the response is real.[33] RNE quantifies the amount of background noise still present in the averaged waveform, it also helps assess whether the recording environment is stable.[33] If no physiological response is present, a low RNE value ensures the technician that the "flat" trace is due to a lack

of response rather than excessive noise obscuring a potential signal.[33] While, a sudden increase in RNE can alert the technician to new noise sources, such as muscle contractions or electrical interference.[33]

Traditionally in routine testing, technicians decide when to stop the averaging process based on a subjective visual assessment of baseline stability and response prominence.[33] However, RNE and Fsp introduce objective statistical criteria for this decision. By enabling recordings to conclude once predefined confidence thresholds are achieved, these methods can shorten acquisition time, promote consistency across operators, and enhance patient comfort by reducing the number of stimuli administered.[33] Mulot (2023) further emphasized that the application of Fsp and RNE improves testing efficiency while increasing diagnostic reliability.[33] Readers are encouraged to review the technical note on Fsp and RNE written by Mulot (2023) in detail.

Moreover, a more robust prognostic accuracy can be achieved through a multimodal approach that integrates BAERs with visual evoked potentials (VEPs) and somatosensory evoked potentials (SEPs), as illustrated in table 11.[34] This combined strategy enables a more comprehensive evaluation of CNS function and has demonstrated superior predictive value for neurological outcomes compared to relying solely on clinical classification or grading systems.[27,34]

Table 11. Outcomes at more than two years of corrected age were evaluated. Fisher's exact test was applied to assess the association between EP results (normal vs. abnormal) and long-term neurological outcomes. Adapted from [27]

Outcome	Normal VEPs	Abnormal VEPs	Total
Normal	7	3	10
Abnormal	1	18	19
Total	8	21	29

Fischer's exact test ($P < 0.001$).

Outcome	Normal SEPs	Abnormal SEPs	Total
Normal	10	0	10
Abnormal	1	18	19
Total	11	18	29

Fischer's exact test ($P < 0.00001$).

Outcome	Normal BAEPs	Abnormal BAEPs	Total
Normal	8	2	10
Abnormal	14	4	18
Total	22	6	28

Fischer's exact test (NS).

5. Conclusion

In neonatal and pediatric care, evoked potentials are uniquely valuable because they provide objective data on brain function that anatomical imaging, such as MRI or CT, cannot offer.[8] BAER is particularly suited for young or critically ill infants in the NICU who are unable to cooperate with traditional behavioral testing.[10] While the clinical environment of the NICU present significant noise and interpretation challenges, the integration of statistical tools like Fsp and RNE effectively overcomes these hurdles.[33] Serial assessment of BAER plays an essential role in neonatal and pediatric care, as it enables clinicians to track ongoing changes in CNS function, differentiating transient from permanent injury. [14, 21] When interpreted with caution using appropriate norms and integrated with clinical assessment and imaging, they provide an unmatched window into the functional health and developmental trajectory of the infant or child brain.[8]

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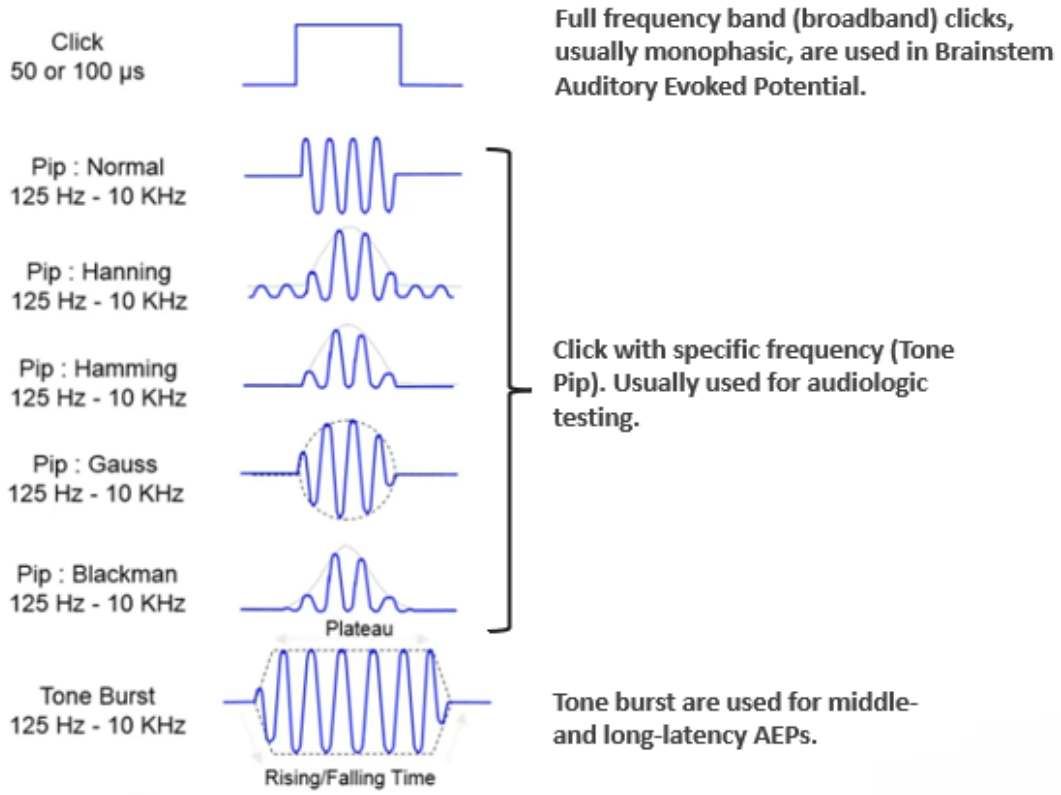
Appendix A

Stimulus Type Pattern

This image illustrates the different acoustic stimulus waveforms or patterns commonly used in auditory evoked potential testing, highlighting the distinction between broadband click stimuli and frequency-specific tone pips and tone bursts.

- **Click Stimulus:** A brief, broadband, monophasic pulse (typically 50 or 100 µs in duration) used to evoke Brainstem Auditory Evoked Potentials. Due to its wide frequency spectrum, it provides synchronous activation of a broad cochlear region.
- **Tone Pips (Windowed):** Short-duration tonal stimuli shaped using mathematical window functions (e.g., Normal, Hanning, Hamming, Gaussian, and Blackman) to concentrate acoustic energy within a specific frequency range (125 Hz to 10 kHz) while reducing spectral splatter.
- **Tone Burst:** A longer sinusoidal waveform characterized by defined rise, plateau, and fall times. Tone bursts are commonly employed for frequency-specific auditory assessment, particularly in the evaluation of later auditory evoked responses.



Adapted and modified from Mulot, A., 2017, Oct 18. Clinical Auditory Evoked Potentials. Neuro Training Academy. https://neuro-training.academy/recorded-eseminars/natus-ep-webinar-clinical-auditory-evoked-potentials/

Appendix B

Stimulus Intensity

Sound intensity is measured in decibels (dB). It describes how loud a sound is compared to a specific reference value. Several terms are used to express sound intensity, depending on the purpose of the measurement:

- Hearing Level (HL): Refers to the average hearing threshold of young adults when tested using 500 µs pure-tone stimuli.
- Normal Hearing Level (nHL): Represents the average hearing threshold of young adults exposed to 100 µs broadband click stimuli. In clinical Brainstem Auditory Evoked Potential testing, nHL is the most frequently used.
- Sensory Level (SL): Indicates the hearing threshold of an individual patient.
- Sound Pressure Level (SPL): Measures the physical pressure of a sound, measured relative to a standard zero reference, expressed in dB SPL. SPL is commonly used to measure the acoustic output of devices such as speakers and headphones.

In BAEP testing, stimulus intensity is often reported in dB nHL, which indicates the number of decibels above the nHL, as it is clinically more meaningful compared to dB SPL. For example, if a 70-dB click stimulus is needed and the average nHL of the individual is 5 dB, the stimulus intensity is set to 75 dB nHL. Note that 75 dB nHL cannot be directly converted to dB SPL without knowing the stimulus type (click, tone burst, etc.), frequency, specific transducer, and calibration correction factors, because the conversion varies with these parameters. The key difference between SPL and HL is that SPL is a physical measurement of sound, whereas HL is a hearing-based measurement referenced to normal human hearing.

Adapted from [1].

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