PEDIATRIC AUDITORY BRAINSTEM RESPONSE ASSESSMENT: THE CROSS-CHECK PRINCIPLE TWENTY YEARS LATER

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In assessing hearing of an infant or young child, the primary objective is to obtain reliable ear-specific and frequency-specific information on auditory function as quickly as possible. In attempting to meet this objective, audiologists must have a high level of confidence in the audiometric measures used. For most children aged 3 years (developmental age) or older, behavioral audiometry, supplemented with immittance and otoacoustic emission measures, usually provides the information required for audiological, educational, and, perhaps, medical management. For children younger than 3 years, especially newborn infants or those children with nonauditory handicapping cond itions who are often referred to as "difficult to test," conventional behavioral audiometry rarely yields complete and reliable information from both ears. In these cases, assessment of the auditory brainstem response (ABR) is the procedure of choice. ABR measurement in children can be used to assess the retrocochlear auditory pathways, as discussed by Dr. Starr elsewhere in this issue of *Seminars in Hearing*. However, the emphasis in pediatric ABR measurement is often on the assessment of peripheral auditory function, the definition of the type of hearing loss (conductive, sensory, or mixed), and the degree and configuration of the hearing loss.

The underlying goal in a pediatric ABR assessment is to predict, or infer as closely as possible, a child's behavioral hearing thresholds. Indeed, within years after Hecox and Galambos (1974) documented the value of ABR in pediatric populations, there were published reports describing the relationship between ABR wave V threshold and behavioral thresholds [e.g., Jerger Mauldin (1978)]. Within recent years, technological advances in commercially available equipment have afforded audiologists more flexibility in test protocols, and more quantitative and accurate strategies for response analysis. However, a quarter of a century after the discovery of the ABR (Jewett & Williston, 1971), most clinical audiologists continue to rely on a click stimulus and ABR wave V to estimate auditory threshold, recognizing that the minimum click stimulus intensity level producing a visually detectable ABR corresponds with behavioral thresholds for tones

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within in the 2000- to 4000-Hz region (Bauch & Olsen, 1986; Pratt & Sohmer, 1978; Hall, 1992), with the best correlation at 3000 Hz (Van der Drift et al., 1989). The click ABR, however, has limited value in estimating auditory threshold levels for lower-frequency or higher-frequency regions. Consequently, a well-formed ABR of reasonably normal latency values may be recorded from patients with communicatively important hearing loss for much of the speech frequency region (500 to 1000 or even 2000 Hz). Also, hearing loss at the upper end of the audiometric frequency region (4000 to 8000 Hz) may escape detection when only a click stimulus is used. Among the numerous approaches reported for measurement of frequency-specific ABRs, two—linear tone-burst stimuli presented in notched noise (Stapells et al., 1990, 1995) and tone-burst stimuli with certain nonlinear windowed rise/fall ramps—have shown the most promise. The tones-in-notched-noise technique is reviewed in detail by Dr. Stapells in this issue of *Seminars in Hearing*. The following discussion is limited to the specially gated tone-burst stimulus technique.

BEYOND AIR-CONDUCTION AND CLICK STIMULATION

Tone-Burst ABRs

The use of tone-burst stimuli in ABR measurement is not a new concept in the area of auditory evoked response assessment. There are several reasons, however, why more audiologists do not include them routinely in their pediatric ABR test battery. First, although tone-burst stimuli with a handful of nonlinear ramping options are readily accessible with modern evoked response systems, there appears to be a general reluctance to take advantage of this feature, perhaps because users are unsure about which specific stimulus characteristics and recording parameters are appropriate. Another deterrent may be associated with the distinct difference in the appearance of the click versus low-frequency tone-burst ABR, and the corresponding difficulty in identifying the broader and less well-defined wave V by using a low-frequency tone-burst stimulus.

Test Protocol

We recommend the tone-burst protocol summarized in Table 1. The main differences between the click versus 500-Hz tone-burst protocols are the stimulus duration (longer for the tone burst), the importance of extending the high-pass filter down to 30 Hz, and a longer analysis time (20 ms). A tone burst at any of the usual audiometric frequencies can be used to record an ABR. In fact, as the stimulus frequency approaches the 3000-Hz region, the tone-burst ABR closely resembles a click ABR. As a rule, however, we'd suggest a 500-Hz tone burst initially, in addition to the click stimulus. Blackman windowing or ramping is selected for generation of the tone burst because it is characterized by relatively little spectral splatter and is, therefore, reasonably frequency specific (Gorga & Thornton, 1989; Hall, 1992; Hall & Mueller, 1997). The speech frequency region is essentially encompassed by the 500-Hz tone burst and click stimulus. Prior to purchasing an ABR system, we advise verifying that these special tonal stimulus options are available.

Response Analysis

An example of a response obtained with a click versus 500-Hz tone-burst stimulus is shown in Figures 1 and 2. Several differences in waveform appearance are clearly apparent. In contrast to the click ABR (Fig. 1), the tone-burst-stimulated waveform lacks a wave I, and often a wave III, component (Fig. 2). Also, wave V is broader and less well defined. Often, the salient feature is the trough following the wave V. Two important points to remember when using a 500-Hz tone-burst stimulus have to do with the relationship of wave V threshold to behavioral threshold. First of all, one must adjust or *calibrate* the *dial* stimulus intensity level so that it corresponds to behavioral threshold. The clinician can as-

TABLE 1. Pediatric Auditory Brainstem Response Test Protocols for Air-Conduction versus Bone-Conduction Click Stimuli and 500-Hz Tone-Burst Stimuli (Air Conduction)

	Air Conduction		*Bone Conduction*
	Clicks	*500-Hz Tone Burst*	*Clicks*
Stimulus parameters			
Transducer	ER-3A insert	ER-3A insert	B-70 oscillator
Duration	0.1 ms (100 μs)	4-ms rise/fall 0-ms plateau	0.1 ms
Ramping (windowing)	Transient	Blackman	Transient
Intensity			
Maximum	95 dB nHL	Variable[a]	55 dB nHL[b]
Minimum	Minimum response level	Minimum response level	Minimum response level
Polarity	Rarefaction	Alternating	Alternating
Rate	27.7/second	27.7/second	11.1/second
Masking	Rarely required	Rarely required	Only if wave I is not observed in ipsilateral electrode array
Acquisition parameters			
Filters	30–3000 Hz	30–3000 Hz	30–3000 Hz
Notch filter	None	None	None
Time window	15 ms	20 ms	15 ms
Number of sweeps	Dependent on SNR[c]	Dependent on SNR	Dependent on SNR

[a]For some evoked response systems, tone-burst stimulus intensity is in dB sound pressure level. The user must find a dial level that is equivalent to 0 dB nHL by finding average behavioral hearing thresholds in normal hearers. The minimum response level for detection of response for tone-burst stimuli typically exceeds 0 dB nHL in normal hearers.

[b]The dial reading for maximum bone-conduction stimulus intensity level may exceed 55 dB, but the effective maximum level will not exceed 55 dB above behavioral hearing threshold (dB nHL) for click stimuli.

[c]The number of sweeps needed to obtain an adequate signal-to-noise ratio (SNR) of approximately 2:1 (the response wave component is about twice as big as background activity) is greatest when noise levels are high and at stimulus intensity levels near auditory threshold and vice versa.

semble a small group of audiometrically normal subjects for this task. Second, for an ABR generated by a 500-Hz tone burst, wave V threshold will still exceed behavioral threshold by 20 to 30 dB in the 500-Hz region (Gorga et al., 1988; Hall, 1992), rather than within 5 to 15 dB above behavioral threshold for click stimuli. We suggest that clinicians actually alter the dial reading through a manufacturer calibration program or determine the appropriate adjustment of intensity and post the difference near the evoked response system. Clinicians might also, for a handy reference, printout and post a few typical tone-burst ABR waveforms recorded at various intensity levels. Keep in mind that the difference between ABR and behavioral threshold, for click or tone-burst stimuli, is always smallest when the signal-to-noise ratio (SNR) is enhanced by increased signal averaging, and when measurement conditions are ideal.

Four points about low-frequency stimuli should be made at this juncture. First, waveform analysis is based almost entirely on the confident identification of a repeatable wave V, rather than precise latency analysis of waves I, III, and V (as for click ABRs). In fact, for a 500-Hz tone-burst ABR, normative data for latency are not required. Second, wave V is invariably broad for low-frequency tone-burst stimuli because the response is generated by less synchronous firing of eighth nerve fibers than for clicks. Synchrony is reduced by the longer stimulus onset time and is reduced with more apical (low frequency) activation of the cochlea. Third, and related to the first and second points, is the absence of a detectable wave I for the tone-burst-generated response. The absence of wave I, which is due to activation of the 2000- to 4000-Hz region, is in turn related to the next, or final, point. Wave V will be observed at a much later latency for a 500-Hz tone burst versus click because the region of the cochlea generating the response is considerably more apical within the cochlea. Two or three millisec-

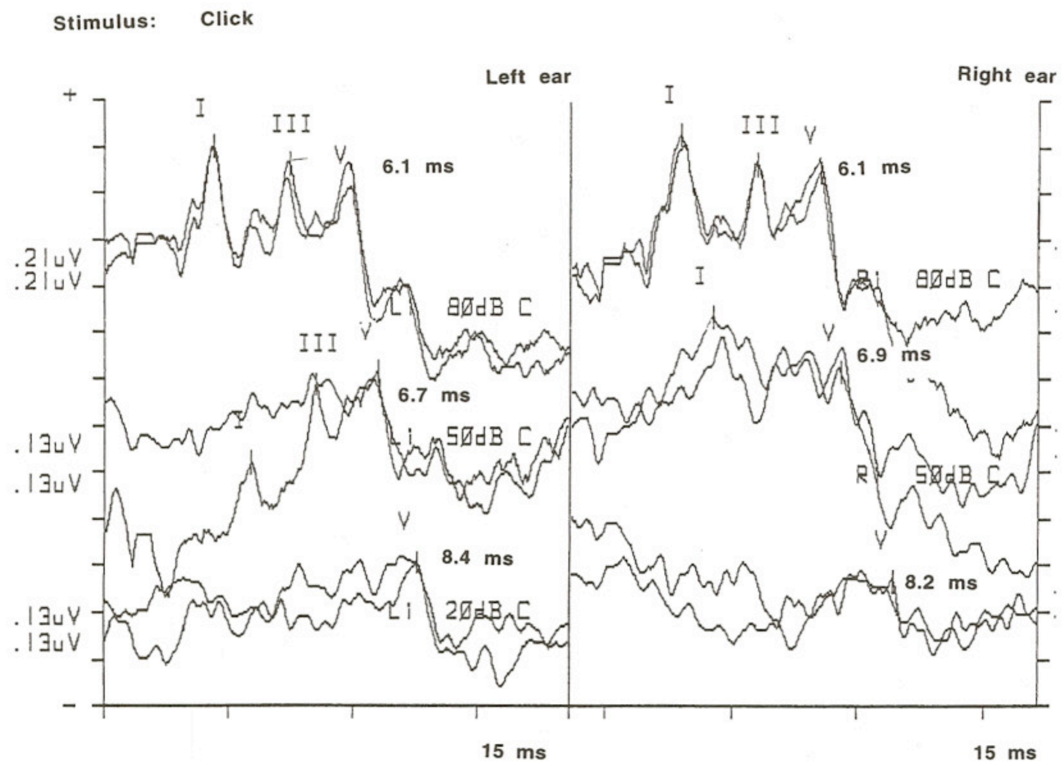


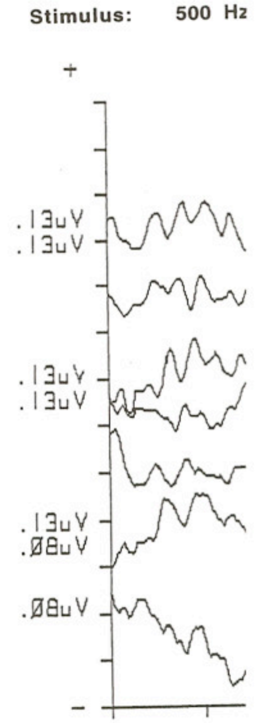
Figure 1. Auditory brainstem response waveforms recorded from an 18-month-old girl by using an air-conduction click stimulus.

onds of travel time are needed to reach this point on the basilar membrane.

Bone Conduction ABRs

In cases where ABR wave V threshold is obtained at an elevated intensity level and, especially, when absolute wave latencies are significantly delayed in comparison to age-corrected normative data for the stimulus intensity level, or where no response to air-conducted clicks or 500-Hz tone bursts is obtained, it is the audiologist's responsibility to attempt to explain the abnormality. Typically, one technical and two pathological explanations may account for increased ABR thresholds and delayed absolute wave latency measures. One technical problem may be that the transducer (or earphone) has moved and the signal is being delivered at a lower intensity level. One pathological factor is a sensorineural hearing loss for the 1000- to 4000-Hz region. As a rule in such cases, wave I is extremely small in amplitude or not detected, and wave V is only slightly delayed in latency, except for intensity levels close to audiometric threshold. Third, and most relevant, is the presence of a conductive pathology and an airbone gap (Hall, 1992; Hall & Mueller, 1997). The delay in ABR latency is due to the effective reduction by the conductive component of the stimulus intensity level activating the cochlea. For example, with a 40-dB conductive component, the ABR for an air-conduction stimulus presented at 80 dB is, in effect, generated by the energy for a 40-dB signal.

ABR stimulation using a bone oscillator placed on the mastoid of the test ear has often been studied and recommended for clinical use with infants since the late 1970s (Jerger & Mauldin, 1978; Hofmann & Flach, 1981; Hooks & Weber, 1984; Hall et al., 1986; Hall, 1992; Yang et al., 1993). Still,



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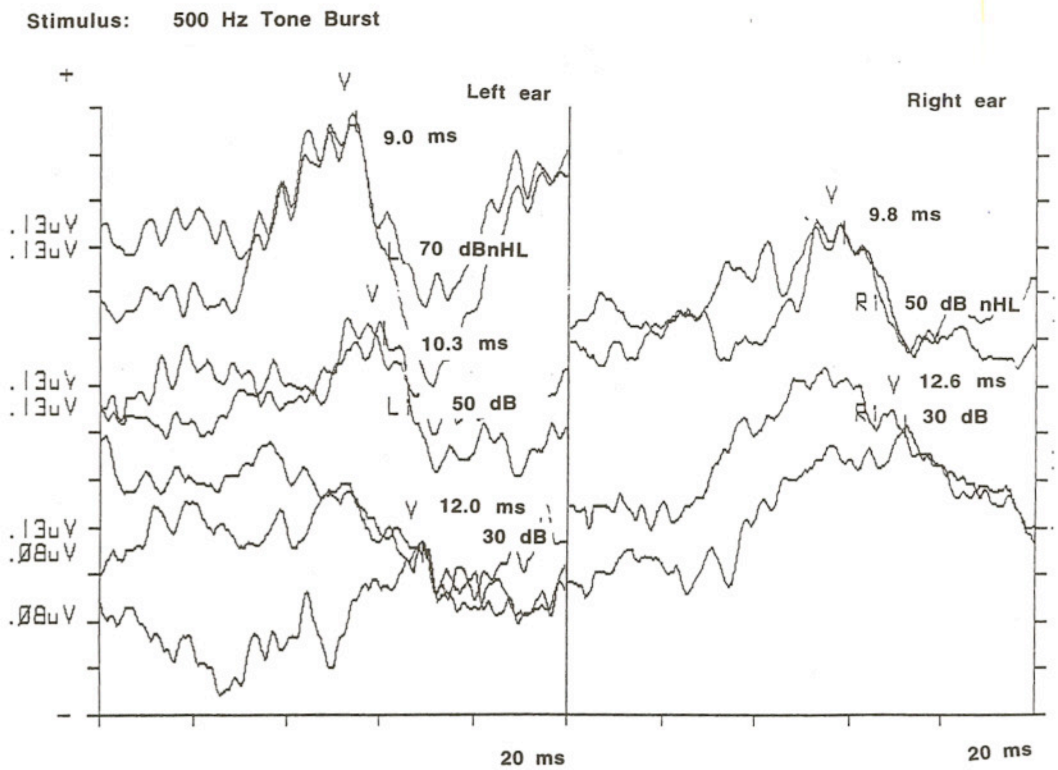

Figure 2. Auditory brainstem response waveforms recorded from an 18-month-old girl by using an air-conduction 500-Hz tone-burst stimulus.

it is a technique that is vastly underutilized. This may be due to several issues, as outlined next.

Bone-Conduction Protocol

In stimulation of an ABR with bone-conduction clicks, the bone vibrator (B-70) is placed on the mastoid of the test ear. Forehead placement is also an option, but the effective maximum intensity level is reduced, and longer wave latencies are recorded (Yang et al., 1987). With placement on the mastoid, or temporal area, several factors must be considered and controlled. The first is stimulus artifact. Because the stimulator is so close in proximity to the inverting electrode (located on the earlobe, not on the mastoid), a large stimulus artifact may be recorded and may obscure the wave I component. This problem is minimized by using a click stimulus of alternating polarity.

A second consideration in bone-conduction ABR is the coupling force of the bone vibrator to the skull. Although the use of an elastic or Velcro band is recommended for consistent bone vibrator coupling with a force of 400 to 500 g (Yang et al., 1991), most clinicians resort to a hand-held method with young children. Several sources of error in measurement are associated with the hand-held method, including pressure variations during measurement and signal damping due to direct vibrator handling, as illustrated in the top portion of Figure 3. According to T. Littman (unpublished data, 1996), signal damping can be effectively reduced by using a single finger in the center of the bone vibrator to hold the oscillator in place (Fig. 3, bottom). In fact, the amplitude of wave V may increase with single-finger placement versus hand holding with two or more fingers (T. Littman, personal communication, 1996). Pressure variations may still occur, however.

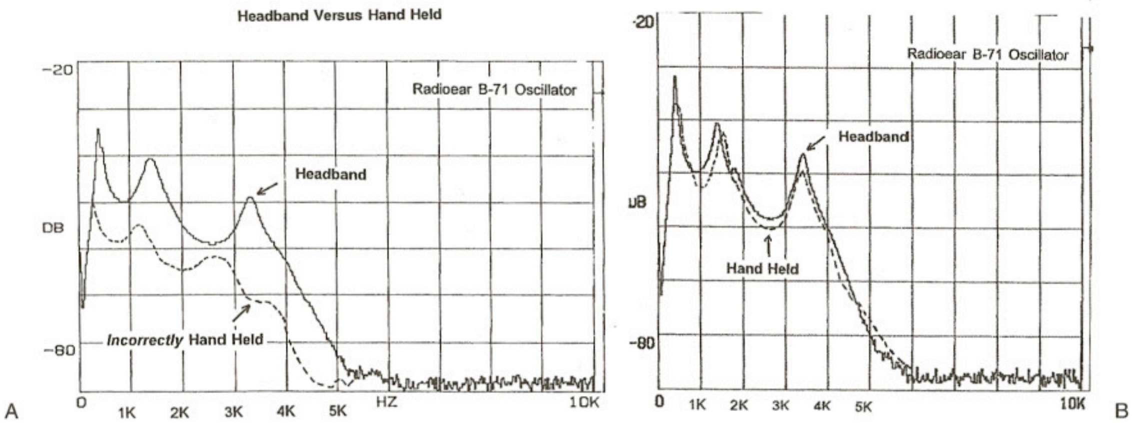

Figure 3. The effect on stimulus spectrum of improperly **(left)** and properly **(right)** hand holding of a bone oscillator for bone-conduction auditory brainstem response measurement. (Courtesy of Tom Littman, Ph.D.)

Once the oscillator is coupled to the head, click stimulation is initiated close to the maximum intensity level (40 to 45 db nHL), and then the intensity of the stimulus is decreased until threshold is estimated, using the same protocol as for air-conduction clicks. Comparing the click thresholds obtained via air and bone conduction will quantify the conductive component. As with air-conducted click stimuli, the frequency region measured using bone-conducted clicks is around 2000 to 3000 Hz (Hall, 1992). Thus, conductive losses in lower frequencies may be underestimated, although ABR absolute wave latencies will still be delayed. The use of bone-conducted tone-burst stimuli has been suggested to obtain frequency-specific responses with bone-conducted tones (Nousak & Stapells, 1992): in this study, Nousak and Stapells described the use of the derived response method to accomplish this task. This method is discussed in detail elsewhere in this issue of *Seminars in Hearing.*

Response Analysis

As with low-frequency tone-burst ABRs, the waveform for bone-conduction ABRs may lack the precision and overall good morphology of air-conduction click-generated waveforms. Repeatability is often less than optimal, probably because of inconsistencies in oscillator placement and pressure, plus the inherently poorer effectiveness in delivery of the transient (0.1 ms) stimulus with a bone oscillator designed for tonal stimuli and through skin and the temporal bone. Two concerns regarding bone-conduction ABR are the limited output of the bone vibrator (maximum, 55 dB nHL), and the relationship between the *dial reading* and actual effective intensity level at the mastoid. It is true that, because of the limited output of the oscillator, the conductive component in moderate to severe mixed hearing impairments will go undetected when ABR measurement is used alone. An absent bone-conduction response to clicks, nevertheless, gives clinicians extremely useful information, and reason to believe, that the child's sensorineural hearing level is abnormal beyond a moderate degree of hearing loss. To have confidence in the measures obtained with the bone oscillator, it is important to know what the dial reading means relative to the actual output of the oscillator. Equipment will vary in this area, and one need only obtain some biological threshold data with click stimulation through the bone oscillator, compared with clicks via air conduction, to determine ac-

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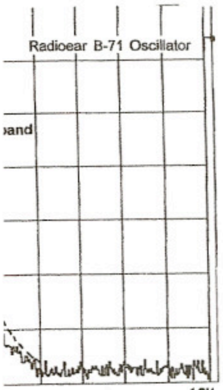

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One common question regarding bone-conduction click ABR assessment is whether to mask the nontest ear. Although interaural attenuation is accurately presumed to be essentially nonexistent (0 dB) in adult patients, Stuart and colleagues (1990) confirmed that interaural attenuation increases to about 15 to 25 dB for children at 1 year of age and is as high as 25 to 35 dB in neonates. Even for older children and adults, the presence of a reliably recorded wave I component from an ipsilateral electrode array confirms that the response is ear specific, much as an ECochG is always ear specific (Hall, 1992; Hall & Mueller, 1997). Thus, the need to mask the nontest ear in many patients is greatly reduced. It is not uncommon with adult patients for waveform morphology to be compromised somewhat with bone-conducted stimuli. In fact, if there is some high-frequency sensory hearing loss, wave V is often the only identifiable component just as it is with lower-intensity air-conducted stimuli. In infants, however, the waveform generated by bone-conducted clicks usually remains well formed and wave I is often identified when sensory functioning is normal. Again, if a wave I is present in the recording obtained when the inverting electrode is located near the mastoid (e.g., earlobe) of the stimulated ear (with the noninverting electrode placed at the forehead), one can be confident that the response is indeed due to stimulation of the test ear (Hall et al., 1986; Hall, 1992). On the other hand, if the wave I component is not present in the waveform, and wave latencies are delayed, masking of the nontest ear may be warranted. A 50 dB nHL, white noise presented via air conduction is usually sufficient to mask the nontest ear.

GENERAL PEDIATRIC ABR TEST STRATEGY

An approach for pediatric ABR assessment is illustrated in Figure 4. The first step in the process is to review available audiological findings and to determine what specific information on auditory function is desired from the ABR assessment. If sedation will be required or is anticipated, additional preparation is essential (see Table 2). An appropriate starting point for the ABR assessment is to present click stimuli via air conduction by using a pediatric insert earphone at a moderate to high intensity level (70 to 80 dB nHL) to verify the presence of waves I, III, and V, minimally, without waking the sleeping child. Infant ABR waveforms may have only these three waves, whereas all ABR waves (I through V) will usually be observed with older children (>18 months). Stimulation at moderate to high intensity levels also enhances the likelihood that absolute and interpeak wave latencies can be calculated. These values should be compared online (during data collection) with normative latency data derived at the same intensity level for the child's particular age group. For children aged 18 months and older, adult latency norms may be used. If no response is obtained at this initial level, the intensity level of the stimulus should be promptly increased to the limits of the equipment in an attempt to detect any response.

Following verification of a reliable click ABR at a moderate to high intensity level, the stimulus intensity is decreased in 20-dB increments, and a response recorded, until wave V is no longer observed. The stimulus intensity level may then be increased by 10 dB in order to bracket threshold, which is defined as the lowest level at which a reliable wave V is detected. It is usually not necessary to verify the presence of a click ABR wave V for intensities of <20 dB nHL. In fact, a time-saving method often used for air-conducted click ABR is to decrease the stimulus intensity to 20 dB nHL immediately following verification of a normal response at the initial intensity level. If wave V is not identified at 20 dB nHL, then the stimulus is increased by 20 dB in order to examine the response at an intermediate level. ABR threshold is then bracketed as previously described. During this process, it

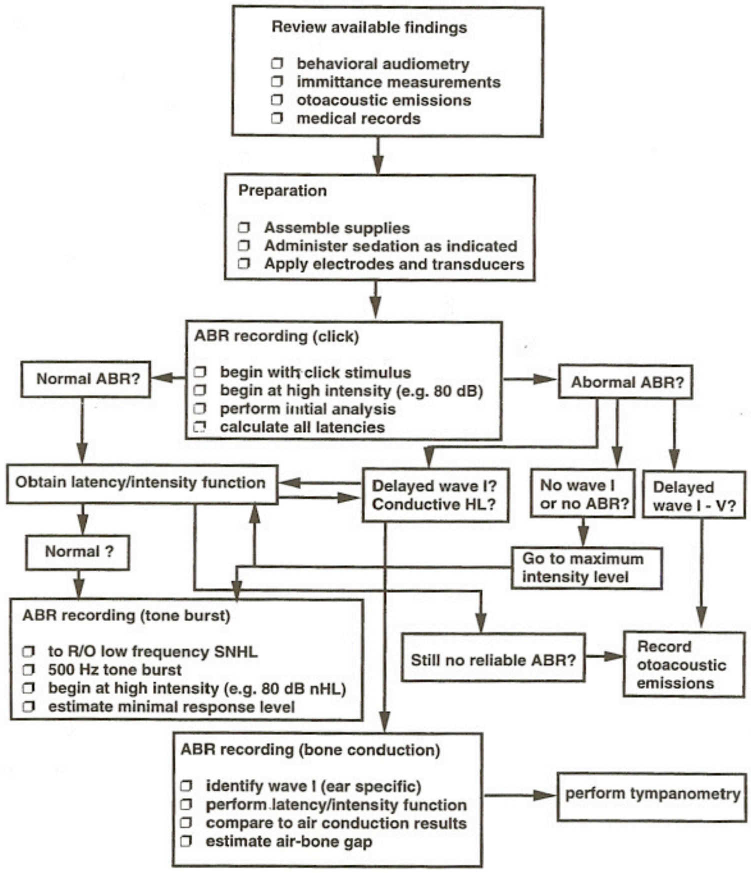


Figure 4. Flowchart summarizing steps in the application of auditory brainstem response (ABR) in the estimation of hearing sensitivity in children.

is very important to identify the wave V component, calculate wave V latency, and compare the latency with appropriate normative data. With some evoked response systems (e.g., Bio-Logic Systems, devices, Mundelein, Illinois), calculated and marked latencies can be displayed instantly on a graphic latency–intensity function. Even when equipment lacks this feature, audiologists can still, during data collection, manually plot latencies on a latency–intensity function form (Hall & Mueller, 1997). One must remember that the mere presence of a response at a particular intensity level (e.g., 30 dB nHL) does not imply that the response latency is within normal limits and does not rule out a hearing loss somewhere within the 1000- to 4000-Hz region.

Whenever the click-generated ABR is markedly abnormal, a sloping hearing loss must be considered. In these cases, a 500-Hz tone-burst stimulus may help to estimate the configuration of the loss as well as the degree of low-frequency hearing loss. With tone-burst stimuli, it generally saves time to begin at a high intensity level in order to facilitate confident identification of wave V. At intensities near threshold, wave V latency may extend to the limits of a 15-ms window, so a 20-ms analysis time is recommended. Once wave V is replicated, the intensity of the stimulus is decreased in order to estimate threshold, keeping in mind the aforementioned intensity considerations unique to tone-burst stimuli. To obtain even more frequency-specific information, otoacoustic emissions should always be considered in

TABLE 2. Checklist to Use When Administering Chloral Hydrate Sedation for Patients Undergoing Pediatric Auditory Brainstem Response (ABR) Assessment

- ✔ Give instructions in advance to the parent or caregiver on clinic policy for obtaining prescription, sleep deprivation, and eating and/or drinking before sedation.
- ✔ Inquire about any prior experience with chloral hydrate sedation. If chloral hydrate sedation failed previously for ABR or another diagnostic procedure, such as computerized tomography. If so, consider intramuscular-injection of Demerol–Phenargan–Thorazine (meperidine–xx–chlorpromazine) combination (a "pediatric cocktail").
- ✔ Verify the prescription from the referring physician for proper dosage.
- ✔ Document the referring physician's complete name, office address, telephone number, and page number.
- ✔ Document (or have the nurse document) any possible contraindications to sedation, any other medications, or any pertinent medical history (e.g., allergies, seizures, respiratory, or heart disorders).
- ✔ Contact the medical support personnel (nurse or physician) upon the patient's arrival and closely follow hospital or facility procedures and policy for conscious sedation.
- ✔ Weigh the patient (note: patient plus caregiver weight minus caregiver weight = patient weight).
- ✔ Convert the patient's weight from pounds to kilograms. Remember 1000 g (1 kg) is equivalent to 2.2 lb.
- ✔ Verify the availability and accessibility (e.g., unlocked) of stocked emergency kit or cart and other required monitoring devices (e.g., pulse oximeter).
- ✔ Unless contraindicated or previously unsuccessful, administer chloral hydrate. The recommended dosage is either 50 mg/kg (milligram of drug per kilogram of body weight) or 75 mg/kg. With the referring physician's written approval, a one-half-dose may be repeated in 45 minutes. The dosage should not exceed 100 mg/kg of body weight or a total of 1000 mg (1 g). Any discrepancies between the written prescription and the chloral hydrate supplied are discussed with the referring physician or on-call attending or resident physician.
- ✔ Chloral hydrate is typically administered orally (drinking from a cup or injected from a syringe without a needle into the mouth) by a nurse.
- ✔ The amount of sedations ingested is documented in writing.
- ✔ Vital signs (respiration, heart rate, and pulse oximetry) are evaluated and monitored before, periodically or continuously during, and always immediately after sedation by a nurse or a physician.
- ✔ After testing, a nurse or physician examines the patient (vital signs and state of arousal) and obtains vital signs every 15 minutes until the patient is stable and responds readily to stimulation.
- ✔ The nurse or tester counsels the parent or caregiver about postsedation care of the patient (according to clinic policy for sedation precautions) and documents this in the medical record. The parent or caregiver is given the telephone number of personnel accepting responsibility for subsequent treatment of the patient.
- ✔ The postsedation status of the patient is documented in the medical records.

From Hall, J.W., III, & Mueller, H.G., III 1997). *The audiologists' desk reference,* vol. I, pp 363–364. San Diego, CA: Singular.

conjunction with tone-burst ABR measurement.

Delayed absolute ABR latencies, especially for wave I, suggest the need for exploration of a possible conductive or mixed hearing loss. Clinicians should, whenever possible, perform tympanometry, immediately after bone-conduction ABR. By plotting a latency–intensity function for both air-conduction and bone-conduction stimuli on the same form, the air–bone gap can be estimated with ABR (Hall, 1992; Hall & Mueller, 1997).

Finally, otoacoustic emissions (OAEs) now are an important component of the pediatric diagnostic test battery (Hall & Mueller, 1997). Among the many applications of OAEs in the pediatric population, perhaps none is as critical as confirming sensory auditory dysfunction in children with abnormal ABR findings. This clinical principal is discussed in the final section of this report.

RECENT ADVANCES IN ABR MEASUREMENT

In pediatric ABR assessment, time is of the essence and invariably determines how much information is gathered regarding the child's auditory status. For infants and children from birth to corrected age 3 to 6 months, pediatric ABRs are usually recorded with the child sleeping naturally, and test time is short and rarely predictable. For children over the age of 6 months, sedation is usually required (refer again to Table 2) to ensure that the child remains inactive during testing (Hall, 1992). However, because conscious sedation does not persist for long periods, auditory information must be obtained as quickly and efficiently as possible. Some time-saving recommendations for pediatric ABR measurement were discussed previously. Additional time-saving techniques have recently become available for use with commercially available equipment.

Decreasing Test Time by Increasing Stimulus Rate

Maximum Length Sequences

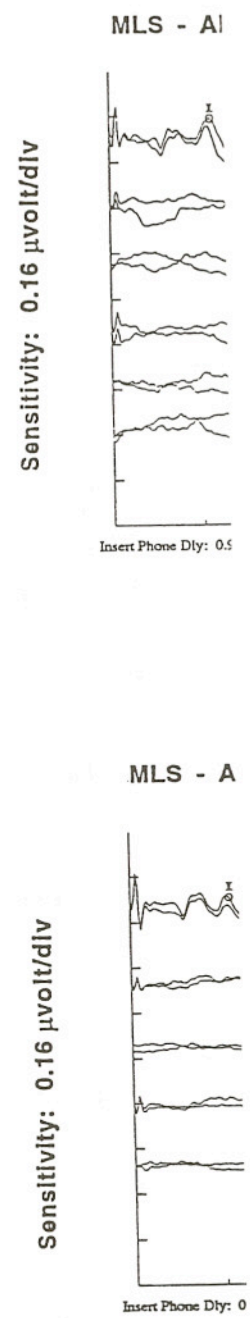
Normally, stimulus rates somewhere between 10 and 30/second are used for clinical measurement of the ABR, and higher stimulus rates are avoided because of their negative effect on wave V amplitude and latency measures (Jewett & Williston, 1971; Don et al., 1977). Because an ABR is averaged from several hundred to several thousand stimulus repetitions, however, the slower the rate of presentation, the longer is the testing time. Increasing the rate of stimulus presentation was first suggested by Eysholdt and Schreiner (1982), who described a stimulus presentation paradigm in which a series of pulses, separated by pseudorandom time intervals, are delivered to the ear. The term used to describe this type of stimulus is *maximum length sequence* or MLS. A detailed description of MLS-ABR is beyond the scope of this report and may be found elsewhere (Hall & Bachmann, 1997; Marsh, 1992; Picton, et al., 1992), but an overview of MLS is presented here.

Using an MLS paradigm, several hundred, and up to 1000, stimuli may be presented to the ear each second (Thornton & Slaven, 1993). Stimulus rates higher than ~500/second are not recommended, however, because of the reduction in waveform morphology and amplitude, as well as the increase in wave V latency that is typically seen with conventional ABR analysis at high stimulus rates. Because the ABR response begins to overlap itself and the SNR is reduced at rates faster than ~70/second, a sophisticated cross-correlational technique must be used in MLS-ABR to disentangle the responses and average them. Thus, using an MLS paradigm that employs a stimulus rate of 500 clicks/second, clinicians can, ideally, collect up to 4000 averages in <10 seconds!

In pediatric ABR assessment, where determination of peripheral auditory status is the main objective, the MLS can significantly reduce test time. An example of an MLS-ABR intensity series is shown in Figure 5. In addition to click MLS stimulation, Picton and colleagues (1992) showed that MLS-ABR can also be used with 500-Hz tone-burst stimuli, as long as the interstimulus interval is >10 ms. The authors reported that threshold values bracketed with 500-Hz MLS were similar to those obtained with conventional 500-Hz tone bursts, that is, ~25 dB above behavioral threshold at 500 Hz (Picton et al., 1992). Several factors must be taken into consideration, however, when using the MLS technique with the pediatric population. First, the time window will need to be increased to 20 or 25 ms to record the response near threshold. Second, wave V may be the only wave present in the response, even at higher intensities, due to the reduction in SNR accompanying the faster stimulus rate. Third, because the SNR is reduced with MLS-ABR, any further decrement in SNR due to subject movement or electromyogenic (EMG) artifact will require additional averaging.

Chained Stimuli

One technique similar to conducting an MLS-ABR intensity series is referred to as the *chained stimulus* method. A chained stimulus includes a series of clicks separated in time by 10 ms. Each successive click in the series differs in intensity from the previous one by 10 or 20 dB, and the responses to each click are stored in two separate buffers at each intensity; *A* buffers store the responses to odd-numbered stimuli and *B* buffers store the responses to even-numbered stimuli. The two separate buffers enable averaging at rapid stimulus rates without the responses overlapping and having to disentangle waveforms. Figure 6 is a



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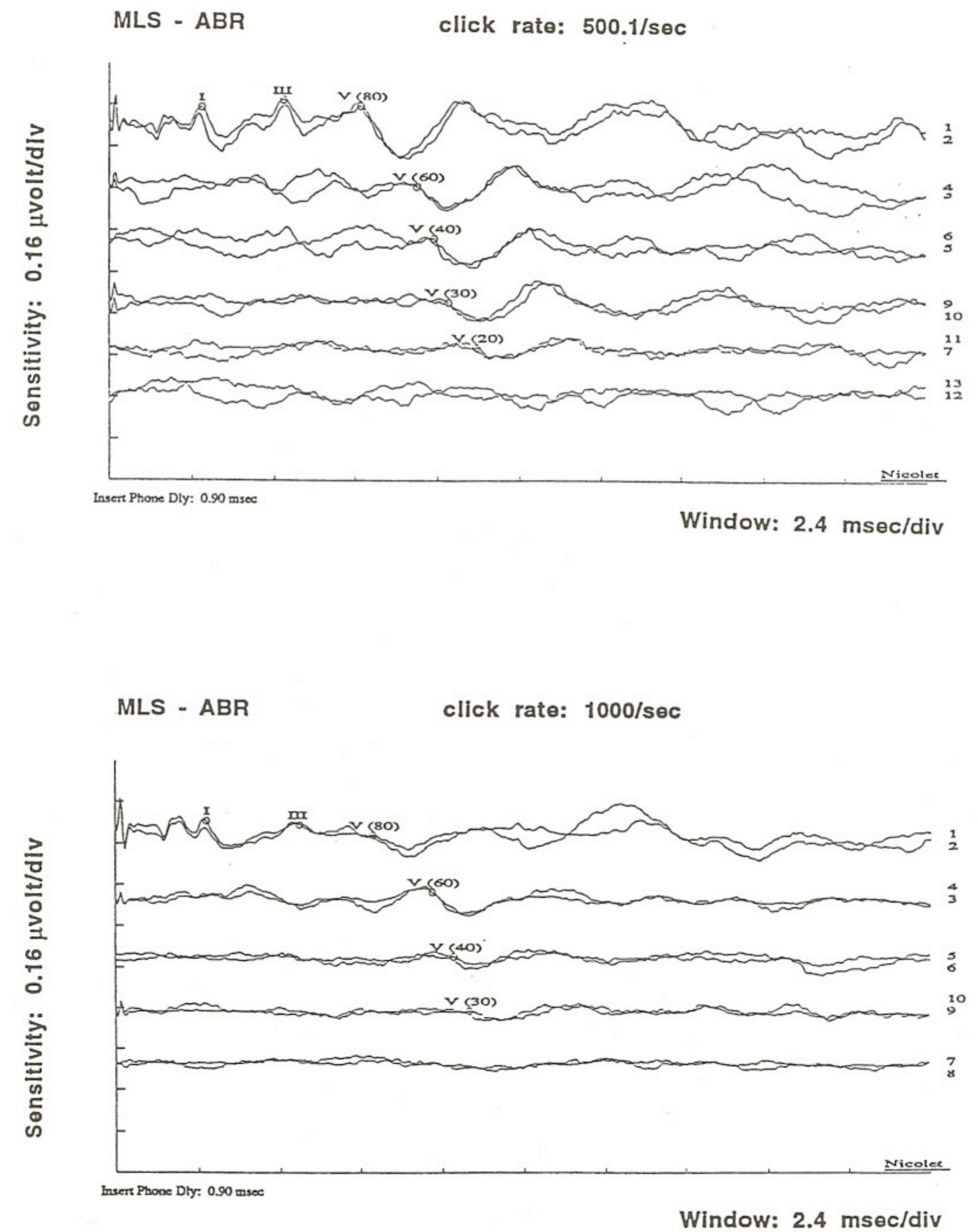

Figure 5. An example of an maximum length sequence–auditory brainstem response (MLS-ABR) intensity series for a normal-hearing adult.

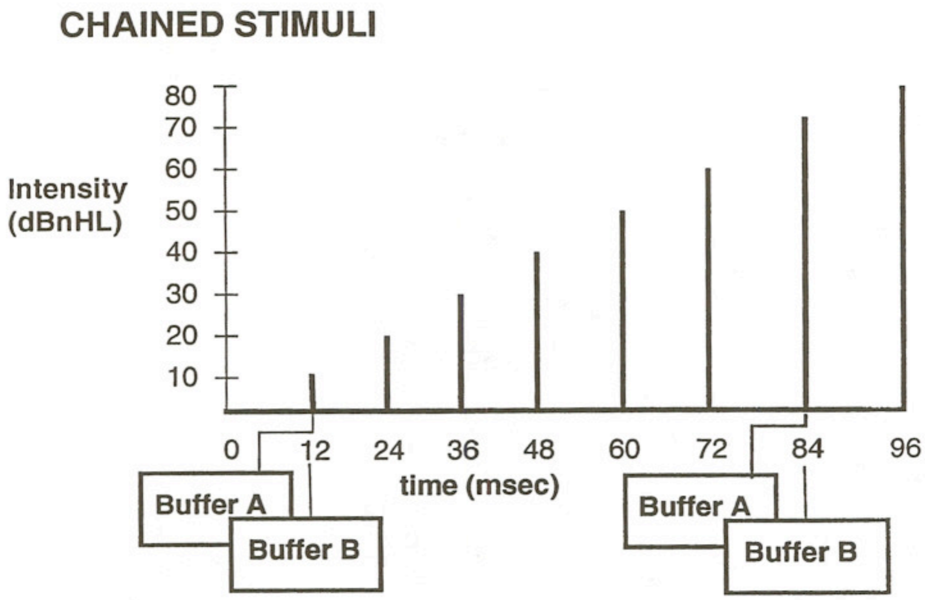

Figure 6. Schematic illustration of a chained stimulus paradigm for use in auditory brainstem response threshold estimation.

schematic of a chained stimulus used in ABR threshold estimation. Threshold estimation using the chained stimulus technique is essentially equivalent to that estimated by conventional ABR, but responses obtained using the chained stimulus method may be collected in as little as 8 minutes per ear (Hammill et al., 1991, 1992).

The potential advantages of the MLS and chained stimuli techniques are obvious, particularly for pediatric ABR application where time is limited. Although the initial research in this area was conducted using laboratory equipment, these techniques are now available for use with some commercially available equipment, such as the Intelligent Hearing Systems, Miami, Florida, SmartScreener ABR unit and the Nicolet Spirit, Madison, Wisconsin.

Reducing Test Time and Increasing Test Objectivity

Another commercially available technique for reducing test time in pediatric ABR assessment is related to improving response detection according to the SNR. Typically, during ABR assessment, continuous visual inspection of the response is required in order to determine the presence or absence of a response. The subjective opinion of the audiologist depends greatly on the SNR; that is, the response must be adequately stable and robust relative to the background EEG or EMG activity before the audiologist will accept it as a true response. With poorer SNRs, increased averaging may be required to reduce the amplitude of the background noise to enable the audiologist to detect the response visually. Increased averaging, however, inevitably increases test time.

Response Detection Through Fsp Calculation

One objective and reliable method for determining true response presence or absence involves calculating the variance of the background noise in the ABR recording and comparing it with a statistical criterion, which provides the audiologist with an indication of the minimum number of averages that will be necessary to detect a response within a specific confidence interval of the *F* distribution (i.e., the 95% or 99% confidence interval). This technique is known as *Fsp,* where *F* refers to the distribution with

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which the variance estimates will be compared, and *sp* corresponds to the *single point* in the ABR samples that will be measured in order to calculate the variance estimate. This method is detailed elsewhere in this issue.

The Fsp calculation is related to the number of sweeps averaged and the intensity level of the stimulus. At higher intensity levels, and where the response is robust relative to the noise, the number of sweeps necessary to determine response presence with 95% confidence is much lower than at intensity levels near threshold, or where the background noise is high relative to the response. In situations where a clear and reliable response is obtained, continued averaging is unnecessary. With the Fsp measure, audiologists can obtain a response and replicate it according to the Fsp value measured; that is, instead of averaging the same number of sweeps to replicate a response, audiologists can average according to the Fsp value obtained for the first record. This may reduce testing time substantially, particularly in quiet recording situations. The utility of Fsp in pediatric ABR assessment, however, may be most helpful in reducing the time associated with threshold estimation. Using a 95% confidence interval of Fsp, audiologists can determine how much to decrease the stimulus intensity level for bracketing threshold; that is, if Fsp criterion is achieved with a relatively small number of averages (e.g., <1000), then the intensity of the stimulus is decreased by 20 dB. If Fsp is achieved only after averaging many sweeps, however, the stimulus intensity is decreased by a factor of 10 dB (Sininger, 1993). The ability to apply this technique during data collection (on-line) is particularly advantageous in reducing test time and increasing efficiency. Further, the objectivity of ABR assessment is increased with Fsp because the determination of response presence or absence is based on a statistical criterion.

NEW PATTERNS OF FINDINGS IN PEDIATRIC AUDIOLOGY

Although first reported in 1978 (Kemp, 1978), otoacoustic emissions have only in recent years begun to assume a pivotal role in pediatric diagnostic auditory assessment. The lag between their introduction and their inclusion in the audiologic test battery was because of the limited variety of commercially-available OAE devices prior to about 1994. Now, five distortion product OAE (DPOAE) devices and one transient OAE (TEOAE) device are FDA-approved for clinical use. As noted below, OAE—either DPOAE or TEOAE—contribute uniquely to pediatric auditory assessment. Indeed, among the dozen or so potential clinical applications of OAE (Hall & Mueller, 1997), their exploitation in pediatric diagnostic auditory assessment is likely to be the most powerful application of OAE. OAE have led to an updated expansion of the "cross-check principle" articulated first by Jerger and Hayes over 20 years ago (Jerger & Hayes, 1976). As an aside, there is no compelling evidence supporting one type of OAE as clearly superior to the other in clinical audiology. When recorded with appropriate test parameters, both TEOAE and DPOAE offer remarkable sensitivity to cochlear deficits secondary to outer hair cell dysfunction (Hall & Mueller, 1997). DPOAE, however, offer several advantages for certain clinical applications. For example, with DPOAE it is possible to assess cochlear function for frequencies across the range of 500 to 8000 Hz, or even 10,000 Hz, a strong feature for monitoring potential ototoxicity. Another practical advantage is that the audiologist may select from the variety of DPOAE devices marketed by major companies that manufacture, distribute, and service audiologic equipment. With the expiration in 1999 of the exclusive license for distribution of the only TEOAE device (the ILO 88 from Otodynamics Ltd), the market for TEOAE instrumentation will no doubt change substantially.

Although the anatomic bases of OAE is the topic of ongoing investigation, it is clear that the cochlea and, in particular, the outer hair cells play a crucial role in their generation (Dallos et al., 1996). OAEs recorded in the external ear canal are sounds reflecting the outward propagation of mechanical energy produced by outer hair cell (OHC) motility. Generation of the OAEs is, apparently, independent of the integrity of the afferent portion of the eighth cranial nerve, and afferent pathways and nuclei within the central nervous system. Peripheral and central components of the efferent (descending) auditory system do exert a distinct influence on OHCs and, therefore, the OAEs. The independence of the OAEs from the afferent auditory system function is a characteristic not shared with other measures of auditory function. For example, to be recorded as normal, pure tone and speech audiometry, acoustic reflex measures, and the ABR all require an intact peripheral and central afferent auditory system. It is logical to expect marked descrepancies between OAEs and these other auditory measures in select patients with etiologies and disorders producing *retro-outer hair cell* auditory dysfunction. These discrepancies might, for example, take the form of normal OAEs with an apparently severe pure tone hearing sensitivity loss, or normal OAE findings in patients from whom no detectable ABR can be recorded.

As audiologists record OAEs more often in diagnostic audiological assessments, unprecedented patterns of auditory findings are being discovered and reported (Norton, 1993; Konradsson, 1996; Monroe et al., 1996; Stein et al., 1996). At the Vanderbilt University Medical Center, during the past 2 years we have encountered over a dozen cases in which OAEs were intact whereas the ABR was initially or permanently markedly abnormal or absent. This clinical experience is increasingly shared by other audiologists who have already incorporated OAEs into their pediatric diagnostic test battery. Some of the more prominent patterns of findings are summarized in Table 3. Clearly, if OAEs are reliably recorded, the absence of an ABR does not invariably imply a profound sensory hearing loss. At the least, OAEs in this type of patient should restrain audiologists from moving immediately to a hearing-aid fitting. This decision should be deferred until more information is available, such as a follow-up ABR or valid behavioral audiometry. Along with others (Stein et al., 1996), we have documented, in a child with hyperbilirubinemia, the reversal of ABR abnormalities, actually the apparent absence of an ABR. OAEs for this child, however, were consistently normal. Monitoring these patients closely is essential. If normal behavioral thresholds are later obtained, then amplification and cochlear implantation is contraindicated. On the other hand, if the ABR remains absent or recorded at only moderate to high stimulus intensity levels and behavioral findings remain abnormal, and the child is also demonstrating speech–language delay, then amplification and the customary associated management (assistive listening devices, family–infant program, and so on) is probably indicated. We can expect more case reports and longitudinal group studies that, in time, will better define these and other patterns of findings and their implications for audiological management. Even though the long-term communicative and neurologic outcome for patients with some of these atypical patterns of findings is not yet clear, the state-of-the-art pediatric test battery now must include OAEs.

Case Report

The second author has followed a series of children with the abnormal ABR versus normal OAE pattern. We'll present a case study to illustrate one variation of this pattern. At the request of his pediatrician, the patient was first evaluated audiologically in his hospital room at 40 weeks gestational age. The assessment consisted of ABR and OAEs. Medical diagnosis was maple syrup urine disease, a serious metabolic disorder. Clinical signs include hypoglycemia, ocular muscle abnormalities, and various neurologic abnormalities, among them epilepsy, spasticity, and mental retardation. As shown in the top portion of Figure 7a, the ABR was markedly abnormal. Only a wave I component was observed bilaterally for stimulus intensity levels of 75 dB nHL down to 30 dB. Distortion product otoacoustic emissions (DPOAEs), however, were entirely within an adult normal region for the right ear (Fig. 7b) and observed for some test frequencies for the left ear. The chart note describing an abnormal ABR and normal OAEs for at

TABLE 3. Pediatric Patterns of Findings for Auditory Brainstem Response (ABR), Otoacoustic Emissions (OAEs), Behavioral Audiometry, and Tympanometry.

Pattern	*ABR*	*OAEs*	*Behavioral*	*Tymp*	*ARs*
Normal	WNL[a] at high and low intensity levels; normal ILIs[b]	WNL	WNL	WNL	WNL
Conductive	Delayed absolute latencies; normal ILIs	Absent	Elevated thresholds	Abnormal	Absent
Cochlear					
OHCs[c]	Variable latency depending on degree of loss; normal ILIs	Absent	Elevated thresholds	WNL	variable
IHCs	Variable latency depending on degree of loss: normal ILIs	WNL	Elevated thresholds	WNL	variable
Central					
Dysynchrony	Absent or wave I only	WNL	Normal thresholds; ? word recognition	WNL	WNL
Metabolic or pathophysiologic	Absent or delayed IWIs	WNL	No response	WNL	Absent

[a]WNL, within normal limits for the patients age group. Parameter is latency for ABR, amplitude for OAEs, peak amplitude and pressure point for tympanometry, and minimal response level for speech and/or tonal stimuli for behavioral audiometry.

[b]ILIs, interwave latency intervals.

[c]OHCs, outer hair cells; IHC, inner hair cells.

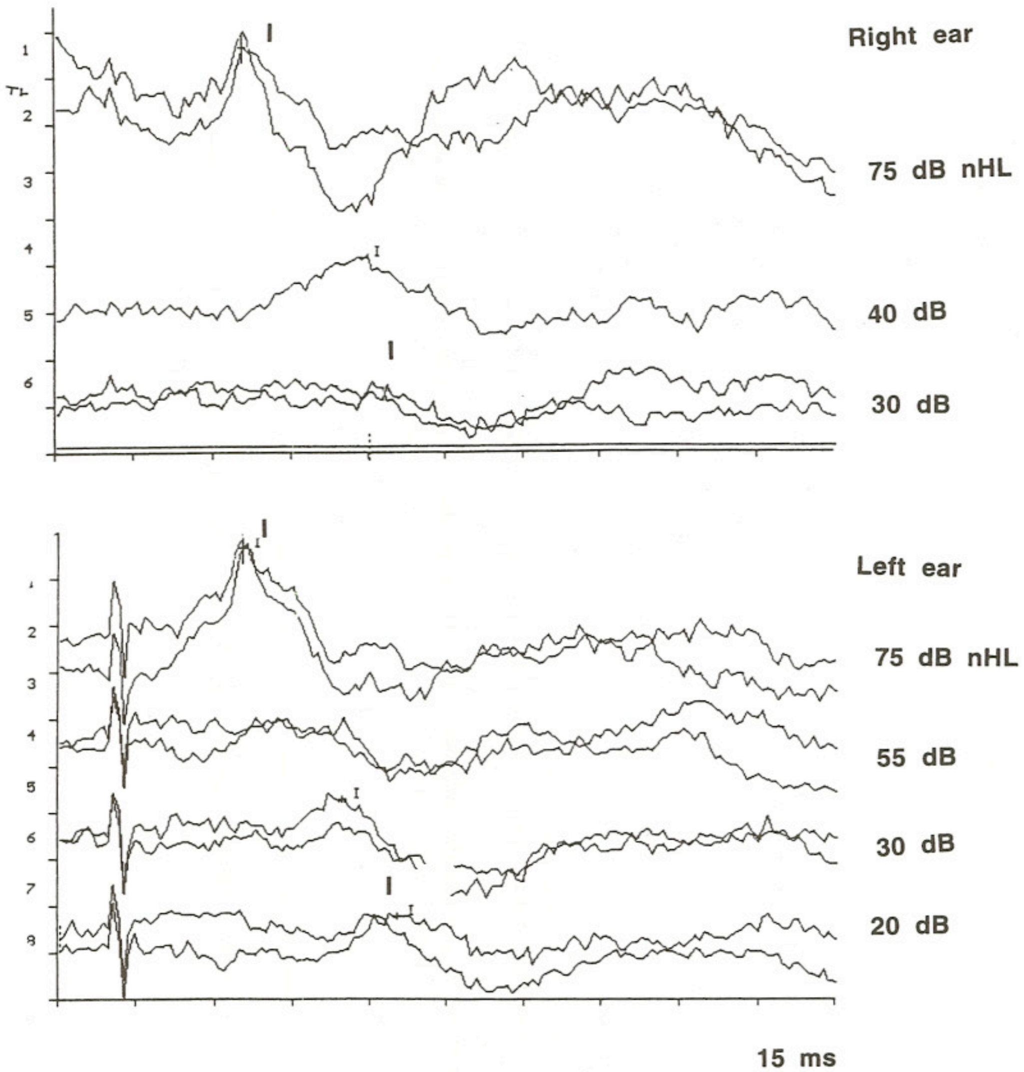

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Figure 7. Auditory brainstem response (ABR) and distortion product otoacoustic emission (DPOAE) results for a term infant with maple syrup urine disease. These initial findings for ABR demonstrated a marked abnormality (A) with only a reliable wave I component. DPOAEs were within normal limits for the right ear and borderline normal for the left ear (B), ABR and DPOAE measurements were made at bedside in the child's hospital room.

least one ear caused some confusion among the patient's physicians. Follow-up ABR and DPOAE findings for this child, 6 weeks later, are illustrated in Figure 8. Later components of the ABR (waves III and V) were now observed bilaterally, although interwave latencies were very delayed, confirming persistent auditory brainstem dysfunction (Fig. 8a). OAEs were normal bilaterally during this test session (Fig. 8b). Tympanograms were normal with a 660-Hz probe tone, confirming normal middle ear function. Amplification was not viewed as an appropriate consideration for this child. He was referred to the Child Development Center for multidisciplinary evaluation and management by pediatric neurology, speech–language pathology, developmental pediatrics, occupational therapy, and physical therapy. We will continue to monitor audiological status, with the goal of obtaining valid behavioral findings.

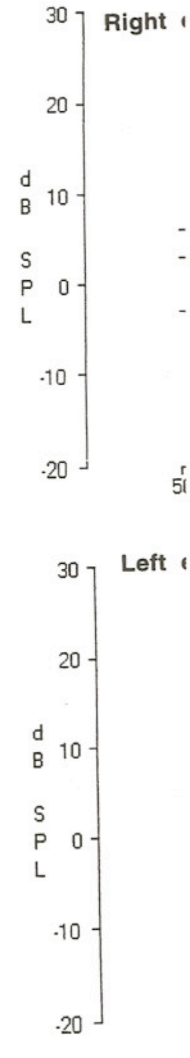

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Figure 7. (*continued*)

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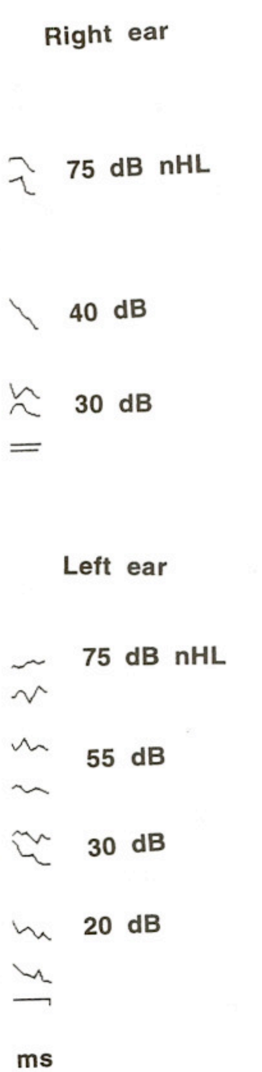

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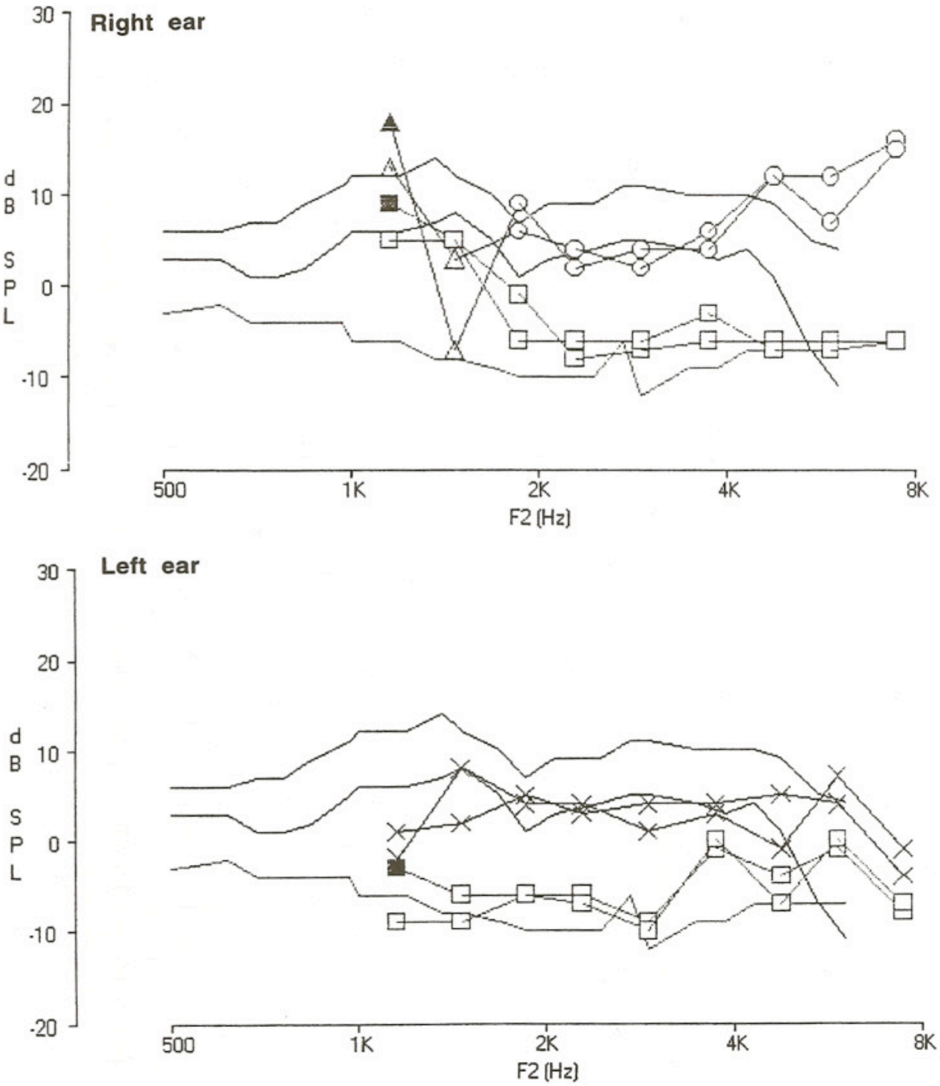

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Figure 7. (*continued*)

CONCLUSION

The challenges associated with pediatric ABR assessment are abundant. The intent of this report is to provide clinicians with current tools and techniques for successfully conducting a pediatric ABR assessment and obtaining adequate information on peripheral and central auditory status as efficiently as possible. As computer and software technology continues to advance, efficiency and accuracy in pediatric ABR assessment will inevitably improve, assuming that audiologists are willing to take advantage of the resources and technology available to them. One new principle of pediatric audiology is now clear—one should not consider amplification or cochlear implantation for any child with traditional evidence of severe sensorineural hearing impairment without first conducting OAE measurement.

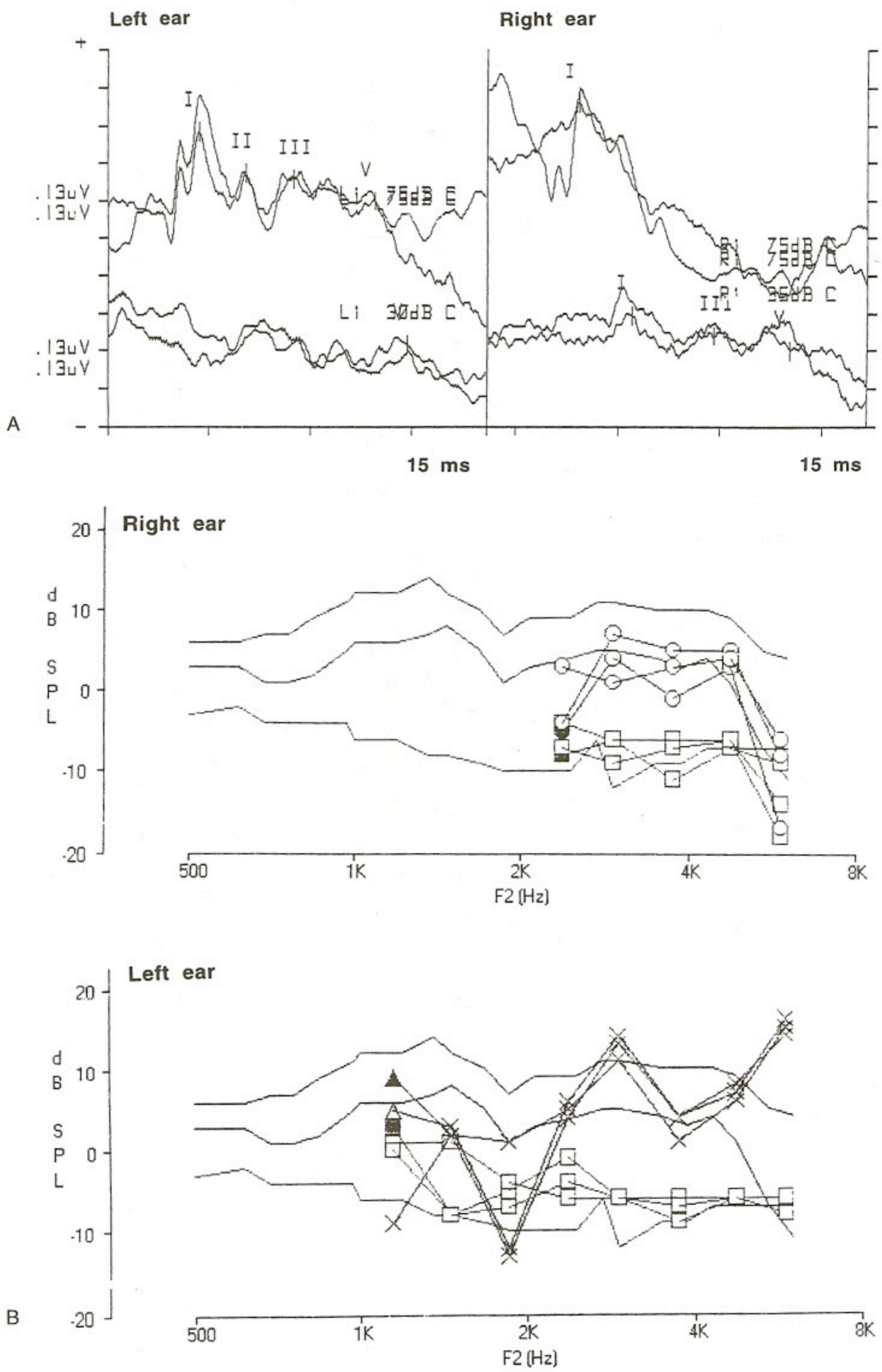

Figure 8. Follow-up findings for the boy with maple syrup urine disease. The auditory brainstem response (ABR) remained markedly abnormal, although later waves (III and V) were observed (A). Distortion product otoacoustic emissions (DPOAEs) were again within normal limits bilaterally (B). The ABR and DPOAE measurements were made in a non-sound-treated audiological clinic room.

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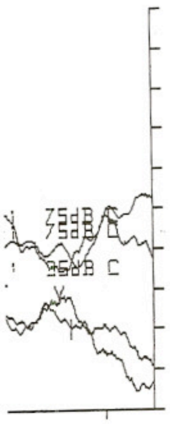

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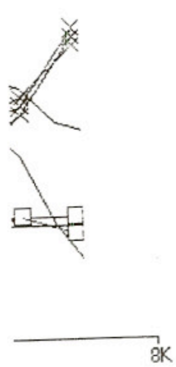

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ARTICLE FOUR

SELF-ASSESSMENT QUESTIONS

1. When recording an ABR using a 500-Hz tone-burst stimulus, which of the following parameters must be adjusted in contrast to recording the response with the conventional click stimulus?
   (a) analysis time window must be increased
   (b) high-pass filter must be extended down to 30 Hz
   (c) Blackmann windowing should be used for stimulus generation to reduce spectral splatter
   (d) All of the above
2. Which of the following does NOT affect Fsp calculation?
   (a) Age of the patient
   (b) Increasing stimulus intensity level
   (c) Reducing biological noise of the patient
   (d) Increasing number of sweeps averaged
3. The clinical applications of evoked otoacoustic emissions include all of the following except
   (a) Monitoring for ototoxicity
   (b) Screening newborns for hearing impairment
   (c) Identifying eighth nerve tumors
   (d) Use as a cross-check in pediatric audiometry to determine the appropriateness of amplification
4. It is important to know the interaural attenuation of a patient who will be undergoing bone-conduction ABR in order to determine whether masking will be needed. When recording a bone-conduction ABR from a neonate, you can assume the interaural attenuation is
   (a) 0 dB
   (b) 25 to 35 dB
   (c) 40 to 50 dB
   (d) 10 dB
5. What are two limitations to recording an ABR when using only a click stimulus?
   (a) May miss a speech–language delay
   (b) May miss a low-frequency hearing loss
   (c) May reduce test time substantially
   (d) May miss a hearing loss due to ototoxicity