Early identification of hearing loss through widespread newborn hearing screening, at long last, allows management of hearing loss to begin during the critical early period after birth. The literature supports the importance of early identification of hearing loss and implementation of management in a timely manner (e.g., Yoshinaga-Itano, Sedey, Coulter and Mehl 1998). Key to this process is the ability to accurately and efficiently quantify hearing sensitivity in infants, just the group of patients who cannot provide reliable behavioral responses to test stimuli.

Table 1. Test battery approach to comprehensive pediatric audiologic assessment. All assessments should include an in-depth case history; testing should be ear-specific with the exception of observation audiometry (column 1). Adapted from Gravel and Hood, 1999.

<table>
<thead>
<tr>
<th>Hair cell</th>
<th>Birth to 4–5 months</th>
<th>5–6 to 24 months</th>
<th>24 months to 4 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evoked OAEs</td>
<td>Tympanometry and Acoustic MEMR</td>
<td>Tympanometry and Acoustic MEMR</td>
<td>Tympanometry and Acoustic MEMR</td>
</tr>
<tr>
<td>Middle ear</td>
<td>Physiologic: ABR – Frequency-specific and click for neuro check</td>
<td>Behavioral: Visual Reinforcement Audiometry</td>
<td>Behavioral: Play audiometry</td>
</tr>
</tbody>
</table>

Determination of hearing sensitivity for infants below 5–6 months of age depends on objective test methods. Objective approaches currently in clinical use with infant populations include otoacoustic emissions (OAE), middle-ear measures including tympanograms and middle-ear muscle reflexes (MEMR), auditory brainstem response (ABR), and auditory steady-state responses (ASSR). A pediatric test battery approach published by Gravel and Hood (1999) recommended inclusion of OAEs and middle-ear measures as standard components of a comprehensive audiologic assessment (figure 1). Determination of auditory sensitivity relies on auditory evoked potentials in infants from birth to at least 4 months of age. In older infants, behavioral testing may also be included.
though an objective measure of sensitivity is used as a cross-check to confirm other test results.

**Otoacoustic Emissions**

OAEs, a sensitive measure of activity related to outer hair cell system function, can be used to distinguish normal hearing or mild hearing loss from more significant sensorineural hearing losses. In the absence of middle-ear problems, one expects OAEs to be present when audiometric sensitivity is better than approximately 35 to 40 dB HL. OAEs are a particularly important diagnostic component in some types of hearing losses, for example auditory neuropathy/dys-synchrony (AN/AD). Due to complex relationships between OAEs and threshold sensitivity, OAEs are not, at present, considered a good measure of hearing thresholds.

**Middle-Ear Muscle Reflexes**

MEMRs provide information about the integrity of the middle-ear muscle reflex arc, involving the eighth cranial nerve, lower brainstem pathways, and seventh cranial nerve, in response to stimulation by high intensity tones. Normal MEMRs are expected when hearing thresholds are better than 60 dB HL in the absence of conductive hearing loss. MEMRs are an important part of the test battery in relation to middle-ear function and the integrity of portions of the neural pathways. As with OAEs, MEMRs are not a good measure of hearing sensitivity.

**Auditory Evoked Potentials**

Auditory evoked potentials (AEPs) from the cochlea to the cortex have several applications in clinical evaluation. Here the focus is on brainstem responses, specifically the ABR and ASSR. The ABR has two primary clinical applications: (1) identification of neurological abnormalities of the eighth cranial nerve and brainstem pathways and (2) estimation of hearing sensitivity based on the presence of responses at various intensity levels.

In pediatric applications, we recommend beginning with an ABR to click stimuli, presented at a high intensity (e.g., starting at 75 dB nHL) in order to evaluate neural synchrony. If good neural synchrony is observed, then we continue with frequency-specific stimuli. In checking neural integrity, it is important to separate cochlear, specifically the cochlear microphonic (CM),

---

**Figure 1.** ABRs demonstrating good neural synchrony in the right and left ears of children with good neural synchrony (left panel) and poor neural synchrony (only CM present) in two children with auditory neuropathy/dys-synchrony (right panel).
from neural components of the response. Cochlear and neural responses are distinguished by comparing ABRs obtained separately with condensation and rarefaction clicks. In this situation, the CM peaks reverse with stimulus polarity changes while neural responses do not reverse but may show slight latency shifts (figure 1). The importance of accurately separating cochlear from neural responses became particularly evident with the identification of AN/AD (Berlin et al. 1998).

Quantifying hearing sensitivity with auditory evoked potentials requires use of frequency-specific stimuli. There are several types of stimuli and approaches to frequency-specific testing. Stimulus types investigated over the years have included filtered clicks, clicks masked with high-pass noise, tonebursts alone, tonebursts with broadband, high-pass, or notched noise, and amplitude and/or frequency modulated tones. Of these, the most commonly used stimuli are tonebursts in ABR paradigms and amplitude and/or frequency modulated tones in ASSR paradigms.

Test protocols may use a combination of clicks and tonebursts, beginning with clicks to assess neural integrity and, if click responses are present, following with tonebursts to assess hearing sensitivity in specific frequency regions. Other test protocols begin with tonebursts at several frequencies and follow up with clicks if a neural synchrony problem is suspected. Regardless of which of these approaches is selected, all recommended protocols include bone-conduction stimuli in addition to air-conduction stimuli to define the "type" of hearing loss, distinguishing conductive from mixed from pure sensory losses.

There is a trade-off between frequency specificity and neural synchrony that underlies the degree of frequency specificity that is possible in evoked potential testing. Brief stimuli such as clicks are broadband and activate a greater portion of the cochlear partition and, consequently, a larger number of neural components. This results in higher amplitude neural responses, but at the loss of frequency specificity. When using evoked potentials to gain information about hearing sensitivity, it is desirable to utilize signals that stimulate narrower regions of the cochlea. The trade-off here is a loss of neural synchrony and a decrease in the ability to see responses in surface recordings if tones have too narrow a frequency focus. While modulating tones for ASSR might suggest a narrower frequency focus, the spectral spread of toneburst and frequency-modulated signals can be somewhat similar, depending on the modulation characteristics employed.

The next consideration addresses the relationship between evoked potential thresholds and behavioral thresholds. This is key information in utilizing evoked potential estimates of hearing sensitivity in the management of hearing loss, including determination of parameters necessary for appropriate amplification. The relationships are influenced by several factors, including differences in stimulus duration and signal-noise characteristics in AEP recordings.

The relationship between toneburst ABR thresholds and behavioral pure-tone thresholds has been described in a number of studies. Stapells (2000) combined the results of a number of these studies meeting specific criteria into a meta-analysis as an initial evaluation of the relationship between ABR thresholds and behavioral thresholds. Results of this analysis showed that, in general, thresholds differed by 10–20 dB across the frequency range of 500 to 4000 Hz with the evoked potential thresholds higher (larger dB value) than the behavioral thresholds. For example, if the lowest level (threshold) where an ABR is seen is 50 dB nHL, then the behavioral threshold would be predicted to be in the range of 30–40 dB HL depending on the frequency of the stimulus and whether or not there is a hearing loss. Data show better agreement between behavioral and ABR thresholds for higher frequencies (than for lower frequencies) and in persons with sensory hearing loss (in contrast to normal hearing).

**Auditory Steady State Responses**

ASSR stimuli typically are continuous tones that are amplitude and/or frequency modulated. Modulated tones are centered on various frequencies, typically from 500 to 4000 Hz, and the EEG response “follows” the modulation envelope of the stimulus. The highest amplitude responses are obtained when the modulation rate is in the region of either 40 Hz or 75–110 Hz. The nervous system responds to the modulation change (e.g., near 40 or 75–110 stimuli per second).

Responses obtained with different modulation rates likely contain contributions from various sources in the auditory system. Lower modulation rates (e.g., 40 Hz) are thought to originate more from cortical sources, while higher modulation rates (e.g., 75–110 Hz) are associated more with brainstem sources (e.g., Kuwada et al. 2002). For the 75–110 Hz responses, the amplitude is larger for the mid-frequencies (1000–2000 Hz) than for lower or higher frequencies (John, Dimitrijevic, van Roon and Picton 2001) while lower modulation rates
(e.g., 40 Hz) show higher amplitude responses in the lower frequencies (Galambos, Makeig and Talmachoff 1980). Furthermore, unlike 40-Hz responses, the higher modulation rate responses can be recorded in infants and in sleeping children (Rickards et al. 1994). Thus, our focus for the remainder of this discussion will be on the higher modulation rate (75–110 Hz) responses.

Studies comparing ASSR and behavioral thresholds in various age groups have shown results similar to those obtained with ABR (e.g., Picton, Dimitrijevic, Perez-Abalo and van Roon 2005; Herdman and Stapells 2003; Rance and Rickards 2002). In general terms, ASSR thresholds are about 10–15 dB higher than behavioral thresholds (where the ASSR threshold has the larger dB value). As noted with the ABR, better agreement between behavioral and ABR thresholds is observed in persons with sensory hearing loss (in contrast to normal hearing).

In the search for protocols and methods that meet clinical needs in the most accurate and efficient manner, a logical question relates to comparisons of ABR and ASSR techniques. Several studies have addressed this issue. As an example, Johnson and Brown (2005) compared ABRs using tonebursts and ASSRs with modulated tones in three groups of adults: those with normal hearing, flat SNHL, and sloping high-frequency SNHL. Their data show similar evoked potential response thresholds from the ABR and ASSR approaches in all three hearing-type groups. Based on these data and other studies, the current expectation is that results from ABR or ASSR will be more similar than different.

Of course, there remains much to learn about the ASSR, just as there was in the early days of utilizing the ABR as a clinical measure. A comprehensive look at the salient issues should include studies of the type noted above in subjects of all ages and for stimuli presented via air as well as bone conduction (e.g., Small and Stapells 2006).

Since brainstem responses such as the ABR are known to mature over the first year of life, it is particularly important in infant applications to understand the developmental changes that occur in the ABR and the ASSR. Studies evaluating the ASSR have shown that ASSR amplitude increased across ages 1–10 months (Lins et al. 1996) and that ASSR thresholds progressively improved in a series of infants evaluated longitudinally at 0, 2, 4 and 6 weeks (Rance and Tomlin 2006).

Recommendation has been made that caution be exercised when interpreting ASSRs obtained to stimuli at high intensity levels. ASSRs can be obtained using higher signal levels than ABRs. There are several reports of ASSRs obtained in patients with profound hearing loss and no behavioral responses (e.g., Gorga et al. 2004; Small and Stapells 2004). Based on these and other reports, it is now suggested that ASSRs obtained at high intensities be interpreted with caution.

There are also some reports of phase-locked ASSRs recorded in patients with auditory neuropathy/dys-synchrony despite the fact that they demonstrate no synchrony in the ABR. The reasons that this might occur presently are not well understood. It is important to understand that ABR and ASSR cannot be used to quantify hearing sensitivity in patients with AN/AD as the ability to utilize these methods for such predictions depends on neural synchrony and integrity of brainstem neural responses.

As noted earlier, we compare condensation and rarification click responses at the beginning of an ABR evaluation to assure that neural synchrony is present and sufficient to use evoked potentials to infer hearing sensitivity. Other centers begin with frequency-specific stimuli and check neural integrity if toneburst responses suggest poor neural synchrony. Both are reasonable approaches as long as one is attuned to the need for neural synchrony to use evoked potentials successfully to infer hearing sensitivity.

**Advantages and Limitations**

As with most test methods, there are advantages and limitations in applying and properly interpreting ABR and high-rate ASSR tests.

Advantages of brainstem auditory evoked potentials, particularly the ABR and ASSR, are that they:

- Can be recorded in infants, children, and difficult-to-test patients
- Can obtain ear-specific and frequency-specific information
- Are not affected by sleep or sedation
- Are objective and non-invasive
- Show good test-retest reliability
- Show better agreement between physiologic and behavioral thresholds in persons with hearing loss than normal hearing

Limitations of the ABR and high-rate ASSR are that they:

- Are not a true test of hearing
  - These methods reflect activity of the peripheral auditory system and brainstem pathways; they are very useful in estimating peripheral sensitivity by virtue of response presence but do not evaluate auditory function at the cortical level.
• Require a quiet and relaxed patient
  – Physiologic and environmental noise can interfere with response acquisition.
• May overestimate mild hearing loss

In addition, limitations specific to ABR include the fact that it is not sensitive to neural disorders above brainstem, and there is subjectivity in marking waveforms and determining thresholds of the response. As noted earlier, limitations specific to the ASSR include caution when testing at high intensities.

One can also compare and contrast some factors between ABR and high-rate ASSR. First, clinical procedures used in identifying the presence of a response differ. While statistical methods exist for evaluating ABR presence (e.g., Elberling and Don 1984), analysis of ABRs and determination of whether or not responses are present remain largely subjective in clinical practice. More objective analysis methods are needed for ABRs to various types of test stimuli, particularly for tonebursts since those responses are more often in need of analysis near threshold where signal-noise ratios are poor. In contrast, ASSR characteristics support the use of different analysis approaches, such as frequency domain analysis, and various algorithms that serve to make determination of response presence more objective. A second contrasting factor relates to the literature that is available to support the use of these responses. The ABR literature, by virtue of many more years of research and clinical application, is large with normal and abnormal responses well defined along with effects of various stimuli, recording parameters and patient characteristics. The ASSR literature is rapidly expanding, but there remains much to learn about the characteristics and applications of the ASSR. For example, additional studies in infants with normal hearing and especially infants with hearing loss, studies with various types and configurations of hearing loss, and comparisons of ASSR and ABR in the same subjects using air- and bone-conduction stimuli should all be helpful in clarifying characteristics and applications. Finally, the ABR is sensitive to brainstem neural pathway integrity and these characteristics are known; the role of ASSR in clinical neural analysis remains to be clarified.

**Summary**

Objective methods, such as ABR and high-rate ASSR, are valuable tools in pediatric diagnostic testing. Whether one begins with behavioral or physiologic methods, depending on the age of the patient, the use of a test battery and the cross-check principle is a critical part of a thorough evaluation. Protocols should contain a combination of physiologic and behavioral test methods. The results from all of the measures need to make sense (agree in terms of current audiologic knowledge). It is critical to use strict procedural and interpretation criteria and “objectify” test methods and interpretation of physiologic and behavioral responses as much as possible. For behavioral testing, using strict criteria (Berlin and Hood 1993) in deciding whether or not a response is present is very important. Methods where the examiner is blinded to the presence of a stimulus, as with some computer-driven systems, in behavioral testing serve to make behavioral testing and decisions about the presence of a response more objective. Equally important is assuring that physiologic test methods are administered in a technically correct manner and accurately interpreted.

And finally… **Remember: Neither ABRs nor high-rate ASSRs are true hearing tests!** Comprehensive evaluation of hearing should ultimately include behavioral testing when an infant reaches an age when accurate behavioral assessment is feasible. However, in the meantime, physiologic testing provides appropriate and comprehensive information that is sufficient to initiate management early in an infant’s life and assure maximal auditory development.

**Acknowledgements**

Appreciation is extended to colleagues at Kresge Hearing Research Laboratory and the Audiology Clinic, Department of Otolaryngology, Louisiana State University Health Sciences Center, New Orleans who contributed to the research cited in this paper: Charles I. Berlin, PhD, Harriet Berlin, MA, Jill Bordinon, MCD, Shanda Brashears Morlet, MCD, Leah Goforth-Barter, MS, Annette Hurley Larmeiu, PhD, Jennifer Jeanfreau, MCD, Bronya Keats, PhD, Li Li, MD, Elizabeth Montgomery, MS, Thierry Morlet, PhD, Kelly Rose Mattingly, MA, Patti St. John, MCD, Sonya Tedesco, MCD, Han Wen, MSBE, and Diane Wilesky, MA. The Hood Lab at Vanderbilt University is also acknowledged: Heather McCaslin, AuD, Andrea Hillock, AuD, Erin Maloff, MS, Christopher Spankovich, AuD, Christine Williams, AuD student/research trainee, and Rita Anelli, AuD student/research trainee. Research has been supported by NIH-NIDCD, Deafness Research Foundation,

References


