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EBP Edge: Innovations in Objective Audiometry for Pediatric Audiologists

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Introduction

The most important numbers to a pediatric audiologist are one,

three, and six. These numbers represent the distilled tenets of the Joint Committee on Infant Hearing guidelines (2007; 2013), which recommend that all newborns should have hearing screened by one month,

an audiologic diagnosis by three months, and an early intervention plan initiated by six months. The clinical tools with which these recommendations are brought to fruition are, by necessity, objective and consist of immittance, otoacoustic emissions, and electrophysiologic measures. When the results of these measures are interpreted holistically, inferences about auditory function can be made. More importantly, hearing aids can be fit based on electrophysiologic thresholds, and infants with hearing loss can gain access to spoken language at a critical time in their language development (Yoshinaga-Itano et al., 2017). It is therefore vitally important that the results of electrophysiologic testing are as accurate as possible.

Over the past two decades, immense progress has been made with regard to improving the accuracy and efficiency of objective audiometry. These achievements can be separated into two main categories: stimulus-based advances and method-based advances. Stimulus-based advances reflect improvements in the stimuli used to generate auditory-evoked potentials in objective audiometry. Method-based advances reflect improvements in tests/techniques that allow for more accurate response detection and estimation of hearing sensitivity over the entire dynamic range of hearing. Despite progress in both areas, many clinics are still using the same electrophysiologic testing strategies that have been in place for 30 years or more.

The goal of this article is to present an evidence-based update describing stimuli and methods that are presently available for improving objective audiometry.

Stimulus-Based Advances
Broadband chirps are the new clicks. Narrowband chirps are the new tone bursts.

For most audiology clinics, the auditory brainstem response (ABR) remains the tool of choice for objective audiometry (and rightfully so). This auditory-evoked potential requires synchronous excitation of many auditory nerve fibers that initiates a subsequent cascade of neural activity from ensembles in the auditory brainstem (Hall, 2015; Hood, 1998). The summation of this neural activity is grossly captured at the level of the scalp in the “waves” of the ABR. Wave V, which is mainly generated by the rostral brainstem, is the waveform feature that is tracked to threshold due to its relative robustness, even at low sensation levels. In order to synchronize neural activity enough to generate voltage that is measurable at the scalp, ABR stimuli must be brief with rapid onsets (i.e., on the order of microseconds for clicks to just a few milliseconds for low-frequency tone bursts). Examples of brief stimuli used to evoke the ABR are clicks (for “broadband stimulation”) and tone bursts (for “frequency-specific stimulation”).

A typical ABR protocol using clicks and tone bursts may look something like the following. After performing immittance and otoacoustic emissions testing, the audiologist begins ABR assessment with a click presented around 80-90 dB nHL in rarefaction, then condensation, polarity. The purpose of this high-intensity click is twofold. The first consideration is whether the morphology of the measured waveform is consistent across polarities or if it inverts (Hood, 2015). The former is an indication that a “true” neural response (i.e., the ABR) has been measured, whereas the latter is an indication that the waveforms in question are pre-neurally generated (i.e., cochlear microphonic). When otoacoustic emissions are present and the only measured evoked potential during ABR recording is cochlear microphonic, auditory neuropathy spectrum disorder is suspected (Berlin et al., 2010; Hood, 2002). If a “true” ABR is measured, this is evidence that *some degree* of auditory function exists through the auditory brainstem. The second consideration is whether the measured ABR has normal or abnormal absolute and interpeak latencies for Waves I, III, and V. This appraisal is based on age-specific normative data (Hood, 1996). Characteristic ABR patterns are seen in different types of hearing loss. For example, delayed absolute latencies starting at Wave I in the presence of normal interpeak latencies suggests conductive hearing loss; if this is observed, bone conduction ABR is warranted (Hall, 2015; Hood, 1998). Normal interpeak latencies and normal or near-normal absolute latencies with poor peak morphology (or missing Waves I and/or III) may suggest a moderate-to-severe or better sensorineural hearing loss. Absent ABRs may indicate severe-to-profound sensorineural hearing loss or a central issue. Prolonged interpeak latencies are

also indicative of a central impairment. Following the diagnostic “snapshot” provided by the click ABR, tone bursts are used to determine frequency-specific thresholds around 500, 1000, 2000, and 4000 Hz. These ABR thresholds can be transformed into estimated behavioral thresholds using correction factors (McCreery et al., 2015; Stapells & Oates, 1997). The estimated audiogram is then used to program hearing aids, most often using the desired sensation level (DSL) algorithm.

The general protocol briefly outlined above works well as a means to objectively characterize infant hearing sensitivity, especially when it is done by a seasoned audiologist with ABR experience. Indeed, there is an extensive literature demonstrating high correlation between tone burst ABR and frequency-specific behavioral thresholds (Stapells, 2000). This means that if we are confident in our ABR results, we can be fairly confident about fitting hearing aids based on the collected information. If this is the case, why do we care about esoteric advances in ABR stimuli? Let us start with a discussion about the limitations of clicks and tone bursts.

The notion that a click is broadband and therefore synchronizes auditory nerve fibers along the entire cochlear length is more aspirational than true. While clicks do contain broadband energy, this energy does not reach different parts of the basilar membrane at the same time because of its tonotopic organization (e.g., Don and Eggermont, 1978). These inherent delays in cochlear activation result in temporal “smearing” of neural activation, which leads to a smaller response amplitude (Elberling & Don, 2008; Don et al., 2005). This concept is demonstrated in Figure 1 (from Smith, 2017). The curve in the top panel demonstrates how long it takes for different frequencies to reach their center frequencies on the basilar membrane. Unsurprisingly, we see that the highest frequencies of a click reach the base quickly (< 1 ms), whereas several milliseconds have elapsed before low-frequency energy reaches the apex. When we pair this temporal delay with the innervation density of auditory nerve fibers in the human cochlea, the result is that the fibers in the 2000-4000 Hz range are highly synchronized, whereas fibers tuned to lower frequencies are not (Figure 1, middle panel). Electrodes placed on the scalp are biased toward detecting synchronous neural activity (bottom panel). Thus, even though a click is a broadband stimulus, it generates a neural response with major contributions from a narrow area of the cochlea. This is why click ABR thresholds are so highly correlated with pure tone thresholds around 2000-4000 Hz (and why they often miss hearing losses outside of this range) (Gorga et al., 2006).

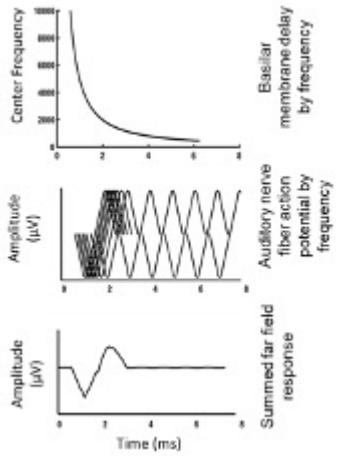

Figure 1. The Effect of Basilar Membrane Delay on Far Field Neural Response

The same issue described above also applies to tone bursts. Although tone bursts are narrowband stimuli (~ 1 octave wide), the energy contained in the tone burst reaches the basilar membrane at different times within a restricted region. Specifically, the higher frequency components of the tone burst reach their center frequencies on the basilar membrane first, followed by middle and low-

frequency components within the narrow band (Rashetswane et al., 2013). These delays are negligible for high-frequency tone bursts; however, the lower the tone burst center frequency becomes, the more temporal smearing occurs (Figure 1, top panel). The consequence of this is more temporal smearing of the ABR for low-frequency tone bursts relative to high-frequency tone bursts. Consequently, tone burst responses reflect neural synchrony from the high frequency "edge" of the narrowband stimulus more than its center frequency (Rashetswane et al., 2013). In summary, although clicks and tone bursts are considered to be broad- and narrowband stimuli, respectively, both are relatively inefficient at generating robust ABRs due to temporal smearing of neural responses. The main consequences of this are longer testing times to resolve the ABR, poorer response signal-to-noise ratios, and less confidence in the results, particularly around threshold and for lower frequencies.

Broadband and narrowband chirps solve this problem, as they are stimuli designed to compensate for basilar membrane delays that result in temporal smearing (Fobel & Dau, 2004). Specifically, chirps begin with low-frequency components first, followed by higher frequency components; the temporal rate at which the instantaneous frequency increases is the inverse of the delay curve demonstrated in Figure 1. Perhaps a more intuitive way to conceptualize this is that the chirp "plays the basilar membrane response in reverse." Because the stimulus itself counteracts basilar membrane delays, the entire area stimulated by the chirp on the basilar membrane is displaced at once, generating a much higher level of neural synchrony (Fobel & Dau, 2004). A comparison between clicks and broadband chirps is shown in Figure 2 along with a schematized depiction showing the time of arrival of each frequency component on specific places along the basilar membrane. Note that although the stimulus waveforms differ, the spectral content of both stimuli is identical. The same is true of narrowband chirps and tone bursts (not pictured). In addition to being spectrally identical, the reference thresholds for each stimulus pair (clicks vs. broadband chirp, tone burst vs. narrowband chirp) are nearly identical. This means that threshold values measured with clicks are equivalent to those measured with broadband chirps and thresholds measured with tone bursts are equivalent to thresholds measured with narrowband chirps without any conversions needed.

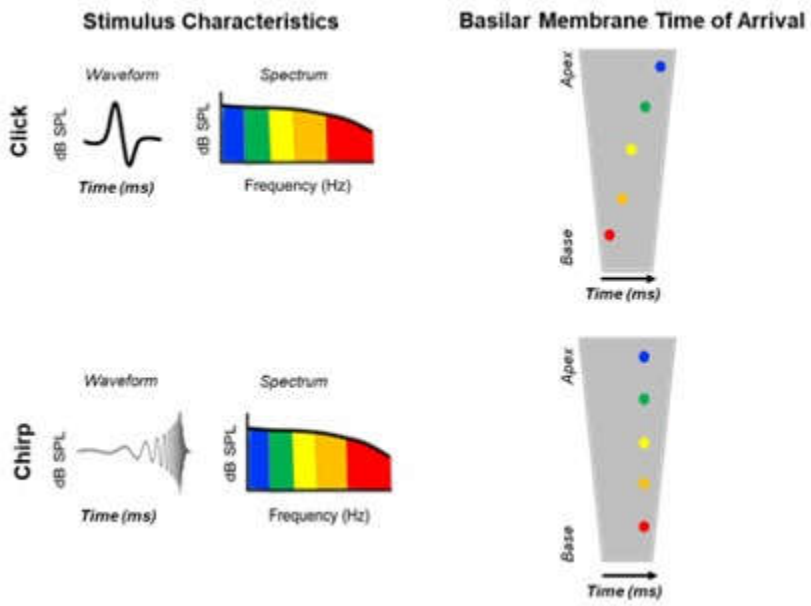

Figure 2. Basilar Membrane Stimulation for Click Chirp and Broadband

A comparison of click and broadband chirp-evoked ABRs in a six-month-old infant are shown in Figure 3. The waveforms represent a level-series function from 70 dB nHL to 20 dB nHL for each stimulus. Readily apparent is the amplitude advantage of the broadband chirp over the click all the

way down to threshold. Note that there is an offset in absolute latency between the click and chirp. This is due to the difference in stimulus duration, and many evoked potentials systems remove this offset for a more familiar ABR display. The amplitude advantage concept demonstrated in this figure has been replicated via air and bone conduction for infants and adults with normal hearing and hearing loss and for narrowband chirps compared to tone bursts (Frank et al., 2017; Kristensen & Elberling, 2012; Rodrigues et al., 2012, 2014; Maloff & Hood, 2014; Vanail et al., 2015). Further, some studies have demonstrated a 50-percent reduction in ABR acquisition time when using chirps versus clicks and tone bursts (Ferm & Lightfoot, 2015; Stuart & Cobbs, 2014). Low-frequency narrowband chirps appear to be far superior at initiating robust ABRs compared to low-frequency tone bursts, which are often difficult to resolve due to the aforementioned temporal smearing issue (Bargan, 2015). Taken together, this evidence suggests that broadband and narrowband chirps are superior stimuli for generating ABRs. More importantly, most modern evoked potentials systems have chirps as stimulus options, meaning they are available for clinical use right now. One way clinicians can begin familiarizing themselves with chirps is to replicate tone burst thresholds using narrowband chirps when time permits. This will foster the transition between familiar and new incrementally and provide real-time opportunities to see the chirp in action.

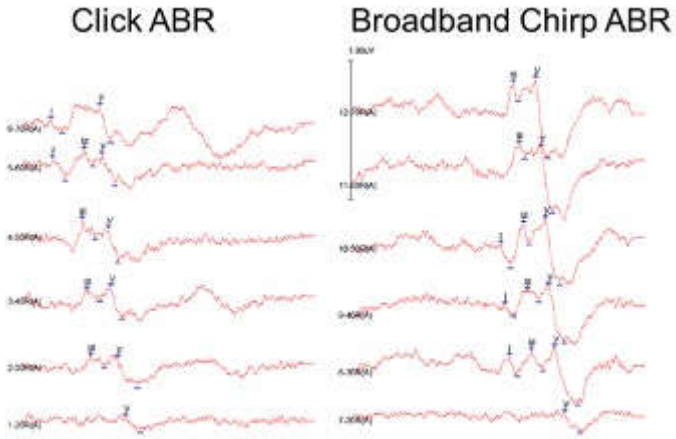

Figure 3. Click versus Broadband Chirp ABR

Method-Based Advances

Auditory Steady State Responses (ASSRs) are more useful than ever before and complement the ABR

There has been much handwringing and editorializing about whether the ABR or ASSR is “better” for objective audiometry. This is a false choice. A more appropriate way to frame this issue is “How can I maximize my objective audiometry protocol by combining strengths of the ABR and ASSR?” Because the ABR is a waveform representing roughly sequential neural activation from the auditory nerve to rostral brainstem, it is an indispensable “snapshot” that is useful for determining site of lesion based on waveform characteristics (as described above). While the ASSR does not provide this view, it does offer a statistically based method for determining accurate air and bone conduction hearing thresholds (Cone-Wesson et al., 2002) and can therefore be used to differentiate normal hearing, conductive hearing loss, and sensorineural hearing loss (but not ANSD). The ASSR offers objective response identification by examining phase coherence to determine whether neural phase locking to frequency and/or amplitude modulated carrier tones is “present” or “absent” at different presentation levels. An advantage of using ASSR for objective audiometry is that multiple frequencies (e.g., 500, 1000, 2000, and 4000 Hz) can be tested in both ears simultaneously, at least when stimulus levels are ~70 dB or less (Korczak et al., 2012; Swanepoel et al., 2004; Tlumak et al., 2007). This greatly reduces test time and removes subjectivity (“peak picking”) from the analysis. For most types of hearing loss, there is a high correlation (r = 0.97) between ABR and ASSR thresholds

(Van Maanen & Stapells, 2005). Further, the variability in the difference between ASSR or ABR thresholds and perceptual thresholds is similar (Johnson & Brown, 2005); this means that as long as we know the appropriate correction factors for ABR and ASSR thresholds, we can estimate hearing sensitivity with roughly equal precision.

Recent advances in ASSR acquisition have improved its performance, particularly for hearing losses in the severe-to-profound range, where ABRs may be less useful. Modern ASSR systems use amplitude-modulated narrowband chirps for the reasons listed above (Sturzbecher et al., 2016); because chirps generate higher neural synchrony within the stimulus bandwidth, the neural response is easier to detect. Additionally, some systems not only measure phase coherence at the frequency or amplitude modulation rate but also at its higher frequency harmonics (e.g., 90, 180, 270). This improves response detection by using more information from the evoked potential.

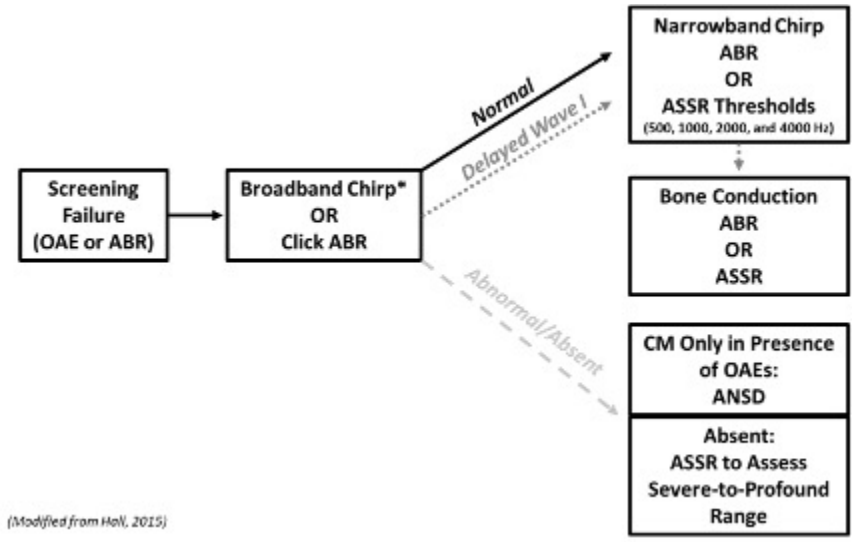

Figure 4. Objective Audiometry Flowchart Using ABR and ASSR. Note that there are many more experiments evaluating the use of a click in diagnosis of ANSD. While recent studies demonstrate that the broadband chirp is suitable for assessing ANSD patients (e.g., Schmidt et al., 2012), it may be premature to fully endorse its use for this purpose until more data is available.

Given some of these differences between ABR and ASSR measurement, how can we leverage the strengths of each response to maximize objective audiometry? Figure 4 depicts a flowchart incorporating the advances in stimulus and methodology described in this article. The rationale for this chart is that the click or broadband chirp ABR is a critical starting point allowing for differentiation between normal hearing, conductive hearing loss, sensorineural hearing loss, and retrocochlear hearing loss/auditory neuropathy spectrum disorder. If the results of the click or broadband chirp ABR are suggestive of normal hearing, conductive hearing loss, or sensorineural hearing loss, an ear-specific threshold search for each frequency 500-4000 Hz commences using the ABR or ASSR with the inclusion of bone conduction as needed. If the click or chirp ABR is abnormal or absent, additional factors must be considered. If only cochlear microphonic is observed in the presence of OAEs, auditory neuropathy is expected. If cochlear microphonic and OAEs are absent, ASSR should be used to assess hearing in the severe-to-profound range. The ASSR is a more suitable tool for analyzing thresholds in this range because the output power of a steady state tone or chirp can be considerably higher than a transient stimulus, where there is a tradeoff between power and duration. By combining using a protocol like the one described in the flowchart, audiologists can leverage the benefits of both types of measurement for more accurate diagnostics across the dynamic range of hearing.

Conclusion

While audiologists are trained to use a variety of evidence-based tools to perform objective audiometry, they often choose familiarity over advances that would improve the outcome of such testing. Modern evoked potentials equipment employs advances in stimuli (i.e., chirps) and measurement techniques (e.g., new ASSR paradigms and detection algorithms), meaning that the fruits of innovation are currently at audiologists' fingertips. I implore audiologists to, at the very least, explore these innovations and decide if they improve diagnostics in their own practice.

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Student Spotlight: Tips on Managing New Start Anxiety

By: Cesar Jaquez, MS, CF-SLP, Graduate Student Representative

Your time has come! It is April, and your time for graduation is finally here! Whether you are an undergraduate student preparing for graduate school or a graduate student looking for clinical fellowships (CFs), it can be kind of scary. It is OK to say that. I don't know about you, but the uncertainty of the future can be anxiety-inducing for me, sometimes. I believe the situations we have the least control over are the most anxiety-inducing; we have seen that with the COVID-19 pandemic. However, there are some ways we can reduce anxiety by managing the situations we can control. Here are some ways you can reduce a little bit of that anxiety, both as an undergraduate, and as a soon-to-be intern:

1. **Research, research, research**. I don't mean conducting a full-blown study. I also don't mean becoming a leading expert in a specific area of our scope. You can prepare for your new start by reading about the latest literature of areas that interest you as an undergraduate. If you're a graduate student, this can mean focusing your reading on specific areas you want to focus on in your CF. By this time, you've had your chance to experience so many areas of our amazing field. You can read material that is more relevant to the setting you want to work in and may make it a more pleasant experience.
2. **Reading about your new institution.** The more you know about your institution, the better prepared you can be to set yourself up for success. As an undergraduate, many of your professors may be involved in research, and, in most cases, their curriculum vitae is public information. Reading your professor's CV may give you an opportunity to think about what