Low-Frequency Hearing and the Auditory Brainstem Response

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How well can you predict low-frequency hearing levels with the ABR?

This question has long been a central issue for the audiometric application of auditory brainstem responses (ABR). For many, there has been a general belief that the ABR does not do a good job in predicting low-frequency hearing levels. This is certainly true when clicks alone are the stimuli used to elicit the ABR. As I will endeavor to show below, however, the ABR to low-frequency short-duration tones can do a reasonable job of predicting low-frequency thresholds, provided careful attention is paid to several technical and interpretation issues.

But first, what about the click-evoked ABR? Only if the hearing is normal or the impairment flat in configuration will the click-ABR predict low-frequency hearing levels with any accuracy. Then again, this is actually the case for prediction of hearing at any specific audiometric frequency. Although the click-ABR provides a general idea of sensitivity, it infrequently provides accurate information about sensitivity for specific frequencies (unless the impairment is flat). This is because the 100-μs click passed through a TDH-49 earphone contains equal acoustic energy from 100 Hz to about 8,000 Hz, with the result that approximately equal contributions are seen to ABR wave V from cochlear regions representing 500 to 8,000 Hz (for review see Stapells, Picton, & Durieux-Smith, 1994). Because human hearing is most sensitive around 2,000 Hz, the ABR in normal hearing (and usually in a flat impairment) is correlated best with this region. However, all bets are off when hearing thresholds are unequal across the 500–8,000 Hz frequency range. ABR threshold may reflect responses from these frequencies in different and often unpredictable ways. For example: In sloping high-frequency impairments, the click-ABR often underestimates the loss in higher frequencies and underestimates residual sensitivity in the low frequencies. Equally important, the click-ABR threshold can miss (or mis-estimate) losses restricted to one frequency region when hearing is normal (or much better) in another region. There are many examples in the literature of large mis-estimations.

So, the conventionally used click-evoked ABR cannot provide reliable estimates of low-frequency hearing (or hearing for other specific frequencies). The solution to this problem is to use more frequency-specific procedures. There are several procedures available (including brief tones, brief tones in ipsilateral masking noise, and clicks in high-pass masking noise), and we have reviewed them elsewhere (Stapells et al., 1994). In general, the results of a large number of studies (at least 25) have indicated that ABRs to 500- to 4,000-Hz brief tones (masked or nonmasked) are recordable down to acceptably low levels (10–30 dB nHL) and provide reasonable estimates of behavioral thresholds. We have found that obtaining ABR recordings to brief tones in ipsilateral notched masking noise provides a reliable and efficient method to obtain ABR thresholds for 500 to 4,000 Hz in adults, children, and infants. These studies contrast with a small number of studies (somewhere between 5 and 10) that have indicated difficulties with tone-evoked ABRs, particularly at 500 Hz. Many of the difficulties encountered in these latter studies can be attributed to one or more of the following problems: high-pass EEG filter settings set too high, ipsilateral masking noise levels too high, recordings obtained in acoustically and electrically noisy environments such as the operating room, averages with too few trials, stimuli that were either too brief or too long, and/or issues concerning waveform interpretation.

There are several important technical considerations for recording the ABR to
low-frequency tones. First, it is important to use a low high-pass EEG filter setting, 20 or 30 Hz or lower (12 dB/octave slope or less). The 100- or 150-Hz high-pass filter setting often employed for clicks is inappropriate for responses to low-frequency tones, and will result in a loss of at least 50% of the response amplitude. Second, because the response is much later than that to a click (especially near threshold), one must use a post-stimulus analysis time of 20–25 ms. Third, both an adequate number of trials per waveform and an adequate number of replications must be recorded. At a minimum, averages of 2,000 trials each are usually required, and we find that three replications (and sometimes four) rather than only two substantially improves response determination.

Fourth, the stimulus must be neither too brief (shorter stimulus results in poorer frequency specificity) nor too long (wave V amplitude decreases sharply after about 5 ms rise time). We have found a total duration of 5 cycles (approximating 2 cycles rise–1 cycle plateau–2 cycles fall, the “2-1-2” tone) to be an adequate compromise. This might be improved using a Blackman window (no plateau). Fifth, the addition of ipsilateral notched noise masking set 20 dB below the peak-to-peak equivalent SPL of the brief tones will help ensure the response originates from the 500-Hz region. White noise masking (i.e., noise with no notch) may be used instead; however, amplitudes will be reduced. This ipsilateral noise masking is primarily important for steeply sloping hearing loss. It is just as important when assessing higher-frequency thresholds as it is for 500 Hz. Currently, the setup for notched noise masking usually requires the use of external filters and mixer/attenuators. Increased demand by clinicians would convince equipment manufacturers to include notched noise and other stimulus options with their clinical ABR equipment. Finally, it is important to calibrate the stimuli (and maskers): brief-tone normal-hearing levels (nHL) are higher than ANSI “HL” levels for pure-tone stimuli. It is a rare clinical evoked potential machine that has brief-tone “0 dB nHL” factory-set dial settings that are close to our calibration levels.

Perhaps most important for ABR recordings to low-frequency tones are the conditions under which they are made and subsequent response interpretations by the clinician. The 500-Hz ABR is very susceptible to electrical noise, both physiological patient-generated noise and external electrical influences. Thus, the patient must almost always be quietly asleep for ABR testing, and the room should be electrically silent. The 500-Hz ABR is also more susceptible to ambient acoustic noise, since ambient noise levels tend to be higher in the lower frequencies. Thus, it is important that such ABR testing be carried out in an appropriately sound-attenuated (and electrically quiet) booth with the evoked potential equipment outside of the booth. Finally, ABRs to 500-Hz tones are more difficult to identify than the click-ABR, and clinicians must become very familiar with them before interpreting them clinically. Rather than the sharp, multi-peaked waveform seen in response to clicks presented at high levels, the ABR to low-frequency tones consists primarily of a longer-latency, rounded wave V to wave V’

**FIGURE 1.** ABR recordings to 500-Hz brief tones presented in notched noise masking, obtained from an infant with normal hearing (NC, left) and from an infant with sensorineural hearing loss (EG, right). Pure-tone behavioral thresholds, indicated for 500 Hz in the boxes, were obtained on follow-up. Traces judged to contain a replicable response are identified by the arrows, which also show the location of ABR wave V and the V-to-V’ transition. Waveforms are plotted with positivity at the vertex as an upwards deflection. Each tracing is the average of 2,000 trials. Stimulus intensities, in dB nHL, are plotted to the left of each waveform.

<table>
<thead>
<tr>
<th>NC, 21 mos</th>
<th>EG, 15 mos</th>
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<tbody>
<tr>
<td>Normal Hearing</td>
<td>SNHL</td>
</tr>
<tr>
<td>Behav = 20 dBHL</td>
<td>Behav = 55 dBHL</td>
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(Also called SN10) transition. Examples of these waveforms are shown in Figure 1. Increased numbers of trials per waveform and increased numbers of replications help considerably in identification.

Assuming one is very familiar with low-frequency ABRs and the recording and stimulation setups are appropriate, what can one expect for prediction of 500-Hz threshold? Recently, we showed a 92% response detectability rate for ABRs to 30 dB nHL 500-Hz tones in a group of normal infants and young children (Stapells, Gravel, & Martin, submitted). Provided they are quietly asleep during testing, infants tested in our laboratory’s sound booth are considered normal at 500 Hz if they show a response to 30 dB nHL 500-Hz tones. Occasionally, an infant with normal hearing will show a 500-Hz ABR threshold of 40 dB nHL. Usually in these cases, the infant’s EEG is noisy during testing, and the result should be interpreted as “normal/near-normal.” Consideration of thresholds for other frequencies and immittance results usually helps in this situation.

Several recent studies have demonstrated strong relationships between 500-Hz brief-tone (in notched noise) ABR thresholds and 500-Hz pure-tone behavioral
thresholds, with correlations of .9 and higher in subjects with normal and impaired hearing (Munnerley, Greville, Purdy, & Keith, 1991; Purdy, Houghton, Keith, & Greville, 1989; Stapells, Gravel, & Martin, submitted; Stapells, Picton, Durieux-Smith, Edwards, & Moran, 1990). Our most recent study, carried out with 88 infants and young children (most referred clinically with sensorineural impairments), found a correlation at 500 Hz of .94 between ABR and follow-up behavioral threshold (Stapells et al., submitted). The 500-Hz ABR thresholds (in dB nHL), on average, were about 10 dB greater than the 500-Hz behavioral thresholds (in dB HL), with no differences for flat versus high-frequency sloping configurations. Approximately 90% of the 500-Hz ABR thresholds were within 20 dB of the behavioral thresholds. Figure 1 shows the ABRs to 500-Hz tones in notched noise obtained from an infant with normal hearing (left), and from an infant with a sensorineural impairment (right).

To conclude, it is possible to predict with reasonable accuracy 500-Hz pure-tone behavioral thresholds from the ABR to 500-Hz brief tones presented in notched noise. This estimate, in dB HL, may be obtained by subtracting 10 dB from the 500-Hz ABR threshold (in dB nHL). By combining ABR thresholds for low-frequency tones with those for 2,000- and/or 4,000-Hz tones, the clinician obtains an estimate of the contour of an impairment and thus improves diagnostic efficacy. Provided the above-mentioned technical factors and interpretation issues are controlled for, these ABR predictions should be within 15 dB of the behavioral threshold for most cases, occasionally (15% or fewer of cases) in error as much as 20–30 dB, and rarely greater than 30 dB in error.

References


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Received November 5, 1993
Accepted February 11, 1994

Key Words: auditory brainstem response, low-frequency hearing, hearing loss, threshold, tones