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ASSESSMENT OF LOW-FREQUENCY HEARING WITH NARROW-BAND CHIRP EVOKED 40-HZ SINUSOIDAL AUDITORY STEADY STATE RESPONSE

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Abstract

Objective—To determine the clinical utility of narrow-band chirp evoked 40-Hz sinusoidal auditory steady state responses (s-ASSR) in the assessment of low-frequency hearing in noisy participants.

Design—Tone bursts and narrow-band chirps were used to respectively evoke auditory brainstem responses (tb-ABR) and 40-Hz s-ASSR thresholds with the Kalman-weighted filtering technique and were compared to behavioral thresholds at 500, 2000, and 4000 Hz. A repeated measure *ANOVA* and post-hoc *t*-tests, and simple regression analyses were performed for each of the three stimulus frequencies.

Study Sample—Thirty young adults aged 18–25 with normal hearing participated in this study.

Results—When 4000 equivalent responses averages were used, the range of mean s-ASSR thresholds from 500, 2000, and 4000 Hz were 17–22 dB lower (better) than when 2000 averages were used. The range of mean tb-ABR thresholds were lower by 11–15 dB for 2000 and 4000 Hz when twice as many equivalent response averages were used, while mean tb-ABR thresholds for 500 Hz were indistinguishable regardless of additional response averaging

Conclusion—Narrow band chirp evoked 40-Hz s-ASSR requires a ~15 dB smaller correction factor than tb-ABR for estimating low-frequency auditory threshold in noisy participants when adequate response averaging is used.

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Keywords

auditory steady state response; auditory brainstem response; Kalman-weighted filtering

INTRODUCTION

Auditory processing of low-frequency sounds is important for neural coding of background noise and speech vowels that carry suprasegmental and higher-order contextual cues that are essential for meaningful sentences (Fogerty and Humes, 2012). Behavioral testing is the “gold standard” for hearing assessment, but in young children it is time consuming and inaccurate at low frequencies (Nozza, 1995; Parry et al., 2003). Thus, objective measures of hearing are useful for children, people with special needs, those with pseudohypacusis, and animal-based experiments that address questions on low-frequency hearing. However, established objective measures with otoacoustic emissions, compound action potentials, auditory brainstem responses (ABR), and auditory steady state responses (ASSR) do not perform adequately for the low-frequency (below ~1 kHz) apical portion of the cochlear spiral (Gorga et al., 1993; Picton, 2007; Sininger, 2007; Spoor and Eggermont, 1976). One reason for this inadequate performance is that low-frequency physiological and environmental noises are hostile to objective measurements of low-frequency hearing. Clinically, over-estimation of low-frequency hearing thresholds can result in gratuitous amplification of low-frequency speech and environmental sounds. Thus, there is a need for optimization of objective measures of low-frequency hearing in hostile testing conditions.

A technique proposed as a solution is the use of Kalman-weighted filtering with *in-situ* pre-amplification of the ABR and ASSR (Sokolov et al., 2006). Together the Kalman-weighted filtering and *in-situ* pre-amplification allow for electrophysiological measurements in awake, non-sedated, adults and children. This technique differs from traditional evoked potential systems in the following ways: 1) An *in-situ* pre-amplifier resides within the housing of the ground electrode and reduces the contribution of electromagnetic and physiological noise in electrophysiological recordings. This unique ground electrode is electromagnetically shielded itself and contains an internal band-pass filter to reduce noise contribution from the brain, heart, and the eyes (Sokolov et al., 2006); 2) The Kalman filter, also known as linear minimum mean-square error filter, calculates the variance between signal and noise from trial to trial and estimates the signal as it correlates with the reference input (Chan et al., 1995). Based on the amount of variance detected within each trial, the quieter sweeps are weighted more than noisier sweeps (Sokolov et al., 2006).

Kalman-weighted filtering and *in-situ* pre-amplification have been used to advance testing protocols by making measurements in a variety of awake, and thus noisy, participants (Bruhn, 2012; Cone and Norrix, 2015; Johnson, 2012; Westhuizen, 2010; Wheeler, 2011; Wiegers, 2013). While these studies demonstrate the advantages of this technique, all of the studies investigated the performance of auditory brainstem responses (ABR) only, which inherently have poor waveform morphology and large correction factors for low-frequency tone-bursts (tb). Over-estimation of tb-ABR thresholds is thought to be a result of poor onset synchrony of low-frequency auditory fibers (Durrant and Ferraro, 1999; Laukli et al., 1988;

Sininger and Abdala, 1996). In our study, we examine an alternative evoked potential for the estimation of low-frequency hearing – the sinusoidal auditory steady-state response.

Sinusoidal ASSR (s-ASSR) were first reported by Galambos and colleagues (1981), who demonstrated that these responses have large amplitudes, even at near-threshold stimulus levels (Korczak et al., 2012). In general, ASSR are generated in response to continuous amplitude and/or frequency modulated signals, and the response waveform mimics the envelope of the stimulus (Korczak et al., 2012). While ASSR have many advantages over tb-ABR, they continue to be under-utilized by clinicians partly due to ambiguity in literature regarding ASSR generators (Hall and Swanepoel, 2009). Many neuroimaging and neurophysiological studies have investigated the generators of the ASSR for different modulation frequencies (Korczak et al., 2012). Specific to the 40-Hz ASSR, there is suggestive evidence that the generation occurs primarily in the auditory cortex with contributions from other sources (Engelien et al., 2000; Herdman et al., 2002; Kuwada et al., 2002; Steinmann and Gutschalk, 2011). Others have reported that the 40-Hz ASSR are unaffected in patients with lesions of the primary auditory cortex and are absent in comatose patients, thus suggesting subcortical or upper brainstem generators (Firsching et al., 1987; Spydel et al., 1985). Moreover, several researchers have reported that 40-Hz ASSR share the same neural generators as auditory middle latency response (Galambos et al., 1981; Kuwada et al., 2002). Although the proposed generators of the 40-Hz ASSR differ between reports, there is general consensus that the ASSR receive input from multiple neural centers regardless of modulation frequency (Korczak et al., 2012).

In our study, we assess the performance of s-ASSR as they compare to tb-ABR in awake participants. We use the 40-Hz modulation frequency because of previous reports that it yields the largest amplitudes in awake participants (Dobie and Wilson, 1998; Linden et al., 1985). The primary purpose of our study is to determine the clinical utility of narrow-band chirp evoked 40-Hz s-ASSR in estimating low-frequency behavioral thresholds as compared to tb-ABR using the Kalman-weighted filtering technique. We express our measurements in terms of correction factors required to estimate behavioral thresholds, which is consistent with routine clinical protocol of subtracting normative correction factors from electrophysiological measurements for estimating hearing in infants and other difficult to test populations. The secondary purpose is to examine the effects of response averaging using the Kalman-weighted technique for our male and female groups as warranted by our preliminary findings (see Methods Overview for details). While the effects of response averaging do not support the primary focus of this study, our preliminary data analysis warranted the examination of these effects. Moreover, the findings on response averaging have important implications for establishing clinical protocols for awake participants.

In our study, we demonstrate proof of concept that s-ASSR can potentially be used as a clinical tool for frequency-specific estimation of low-frequency hearing in awake patients, in which tb-ABR cannot be recorded successfully. Despite good correlation of ASSR with behavioral thresholds for hearing-impaired individuals (Stueve and O'Rourke, 2003; Tlumak et al., 2007; Van der Reijden et al., 2006), studies demonstrate a lack of correlation between behavioral and electrophysiological measurements in normal hearing individuals; this is due to the large amount of unexplained variability observed in electrophysiological thresholds in

normal ears (Scherf et al., 2006; Thumak et al., 2007; Tomlin et al., 2006; Van Maanen and Stapells, 2005). As with these studies, we do not expect to find correlations between behavioral and electrophysiological thresholds due to the limited range of behavioral thresholds of normal ears. Nonetheless, our normative correction factors from two different amounts of response averaging can be used to guide further research and clinical procedures.

METHODS

Participants

Thirty young adults (15 males and 15 females), ages 18–25, were recruited from Missouri State University and the Springfield, Missouri area. All participants had normal hearing and middle ear status. All procedures were approved by Missouri State University's Institutional Review Board for the protection of human participants (approval #13-0273).

Overview

Narrow-band chirp evoked 40-Hz s-ASSR, 40-Hz automated ASSR (a-ASSR), and tb-ABR thresholds were obtained using the Kalman-weighted filtering technique and compared to behavioral thresholds. Effects of equivalent response averaging were determined by comparing Group 1 data that consisted of 2000 equivalent response averages from 15 females and Group 2 data that consisted of 4000 equivalent response averages from 15 males. Equivalent response averaging means that more responses may have been recorded but only certain responses were accepted based on noise level.

Our original study design included the comparison males and females measurements made from the same number of equivalent response averaging. However, we first made measurements from female participants and conducted a preliminary analysis before collecting data from our male participants. The preliminary analysis showed that s-ASSR thresholds were much higher (worse) than expected from previous experience and the literature, demonstrating that an additional number of equivalent response averages was needed as we progressed through the next phase of data collection. Measurements from male ears were thus made from twice as many equivalent response averages. Unfortunately, additional female data could not be collected with a greater number of averages because of limited access to the loaned equipment. Analysis of the gender effect revealed no differences between males and females for tests that were not averaging dependent, i.e., behavioral thresholds and automated ASSR measurements (see Figure 1). Based on these findings, it is reasonable to remove gender as a major confounding variable in our study. Thus, throughout this report we refer to our groups as “Group 1” and “Group 2” respectively, instead of “female” and “male” because the evolution of our study design allowed us to quantify the effects of number of equivalent response averages after removing gender as a major confounding variable.

Procedures

Pure tone air-conduction thresholds were measured for 500, 2000, and 4000 Hz (TDH-39 headphones; GSI AudioStar Pro, Grason Stadler, Eden Prairie, MN). 226-Hz tympanometry (GSI Tympstar) was performed to include only those ears with Jerger Type A tympanograms

(static acoustic admittance (Y_{tm}) = 0.3 mmhos, equivalent ear canal volume (V_{ea}) = 1.2 cc, and tympanic peak pressure = ± 100 daPa). For electrophysiological testing, skin on the high forehead, low forehead, and right mastoid were scrubbed, and disposable, pre-gelled electrodes were placed. Larger 40-Hz ASSR amplitudes can be obtained with ipsilateral, not contralateral, electrode montages (Kaf and Danesh, 2008). Therefore, the electrode montage was right mastoid (M_2) inverting, high-forehead (Fz) non-inverting, and mid-forehead (Fpz) ground. Impedances were kept under 5 k Ω . ER-3A insert earphone transducer calibrated to manufacturer's specifications was used for ipsilateral stimulus presentation in the right ear. A Vivosonic Integrity V500 Evoked Potentials System Version 7.1 with a VL0236 VivoLink Bluetooth interface was used for tb-ABR and s-ASSR thresholds (Vivosonic, Inc., Toronto, Ontario, Canada). 40-Hz automated ASSR (a-ASSR) measurements were also made. All participants were reclined in a chair with their necks supported.

Participants were awake and encouraged to read a book or play games on their phone or laptop to simulate a noisy test environment. EEG was maintained within ± 50 μ V to ensure participants were relaxed but alert. The order of stimulus frequencies and test type were varied between participants and counterbalanced between groups. After initial analysis by the experimenter, ABR and ASSR waveforms were analyzed by two additional raters experienced in auditory electrophysiology to measure electrophysiologic thresholds. In the event of rater disagreement, electrophysiologic thresholds were determined to be the level at which two out of three raters agreed. Behavioral thresholds were not available during ABR and ASSR recordings or analysis to eliminate biases. The overall inter-rater agreement for tb-ABR and s-ASSR subjective threshold determination was 80% for all frequencies, indicating high consensus between three independent raters for both measures. Note: 40-Hz s-ASSR data requires subjective interpretation, whereas 40-Hz a-ASSR data cannot be interpreted by raters, as it is an automatic measure.

Data Collection

For tb-ABR measurements, rarefaction tone bursts (2.5-0-2.5 cycle [rise/plateau/fall]) of 500, 2000, and 4000 Hz were presented at 27.5/sec. For s-ASSR measurements, we used narrow-band chirps centered at 500, 2000, and 4000 Hz that were constructed and implemented for ASSR measurements similar to Elberling et al. (2007) and Elberling and Don (2008), which is slightly different than the chirp stimuli we have previously used (Chertoff et al., 2010). tb-ABR waveforms were filtered between 30–1500 Hz with a 12 dB/octave high pass and 24 dB/octave low pass filter. s-ASSR waveforms were low-pass filtered with a 12dB/octave cut-off at 45 Hz, which allowed us to capture the low-frequency response of the 40-Hz s-ASSR. tb-ABR and s-ASSR stimuli were initially presented at 60 dB nHL, and then a “20 dB down 10 dB up” bracketing procedure was used followed by a “10 dB down 5 dB up” procedure near threshold. Measurements were made while monitoring the real-time waveform repeatability and response presence. To address the possibility of differences between our male and female participants, 40-Hz a-ASSR measurements were made from narrow-band chirps centered at 500, 2000, and 4000 Hz with a bracketing procedure with 20 dB HL being the lowest possible threshold. Stimuli were initially presented at 50 dB HL, decreased by 20 dB if a response was present, decreased by another 10 dB if a response was present at 30 dB HL. Otherwise, stimuli were increased by

10 dB at any level if a response was not detected within 6 minutes. Response detection for a-ASSR depended on relatively stable EEG within $\pm 5 \mu\text{V}$. Unlike tb-ABR and s-ASSR, participants' physical activity was therefore limited for a-ASSR.

Statistical Analysis

To determine the accuracy of s-ASSR and tb-ABR thresholds compared to behavioral thresholds and to test the influence of the number of equivalent response averages, a mixed factorial repeated measures analysis of variance (*ANOVA*) was conducted in SPSS at each of the three stimulus frequencies for test type (tb-ABR, 40-Hz s-ASSR, and behavioral threshold) and group (Group 1 vs. Group 2). Post-hoc paired-samples *t*-tests were performed on the main effect of test type for each frequency. We quantified the correlation between measurements from each test type and stimulus frequency with Pearson's *r*. Although data were collected from 15 females (Group 1) and 15 males (Group 2), statistical analyses were performed on 15 females and 14 males because tb-ABR data for one male subject was not obtained due to equipment malfunction. For the a-ASSR screening measurements, data were analyzed using descriptive statistics only. a-ASSR data from a different male subject was excluded because the *Z* score was greater than ± 3 , identifying his data as a univariate outlier. Thus, similar to s-ASSR analyses, a-ASSR analyses included 15 females (Group 1) and 14 males (Group 2).

RESULTS

We evaluated the possibility that measurements differ between males and females: Behavioral and a-ASSR thresholds were compared (Fig. 1). Unlike s-ASSR measurements described below, the amount of equivalent response averaging for a-ASSR measurements did not vary between Groups 1 and 2. The range of average thresholds for a-ASSR measurements at 500, 2000, and 4000 Hz was 20–26 dB greater than behavioral thresholds for both Groups 1 and 2. Both behavioral and a-ASSR thresholds were not significantly different between Groups 1 and 2. Thus, *s-ASSR results described below are due to differences in number of equivalent response averages, not gender.*

Due to higher signal-to-noise ratio with additional averaging, Group 2 overall thresholds were significantly lower (better) than Group 1 thresholds. (Fig. 2, and Tables 1 and 2). For Groups 1 and 2, thresholds of tb-ABR and s-ASSR measurements were significantly higher than behavioral thresholds for all stimulus frequencies – a result consistent with Tomlin et al. (2006). Correction factors for tb-ABR and s-ASSR thresholds were calculated by subtracting behavioral thresholds from tb-ABR and s-ASSR thresholds. The mean s-ASSR correction factor across frequency for Group 2 (16.33 ± 7.19 dB) was similar with that reported by Van Maanen and Stapells (2005). The 500 Hz tb-ABR correction factor was high (31 dB) for Groups 1 and 2, consistent with other reports of high correction factors for tb-ABR estimates of 500 Hz behavioral threshold (Marcoux, 2011; Stapells, 2000; Stapells and Oates, 1997). The mean tb-ABR correction factors for 2000 Hz and 4000 Hz were respectively 15 and 11 dB for Group 2, and 28 and 29 dB for Group 1. The range of mean s-ASSR thresholds for 500, 2000, and 4000 Hz was 13–16 dB for Group 2 and 35 dB for Group 1. Group 1 tb-ABR and s-ASSR thresholds were not significantly different for 500

and 2000 Hz, and tb-ABR thresholds were lower for 4000 Hz but this did not reach statistical significance ($p = 0.05$). For Group 2, tb-ABR and s-ASSR thresholds for 2000 and 4000 Hz were not significantly different but tb-ABR thresholds were significantly higher for 500 Hz. Moreover, Figure 2 shows that there is greater relative variance as determined by standard deviation of the electrophysiological responses for Group 1 than for Group 2. The overall findings of *lower s-ASSR thresholds, lower correction factors and smaller standard deviations associated with greater equivalent response averaging, and indistinguishable tb-ABR thresholds regardless of number of averages, demonstrates that s-ASSR performs better than tb-ABR for estimating auditory thresholds at low frequencies.*

Correlations between behavioral, tb-ABR, and s-ASSR thresholds

There were no significant correlations between behavioral and electrophysiological thresholds for either group at any frequency (Fig. 3a–f). Thresholds of our two electrophysiologic measurements did not significantly correlate for Group 1 at any frequency (Fig. 3g–i). tb-ABR and s-ASSR thresholds at 2000 and 4000 Hz were significantly correlated for Group 2 (Fig. 3h,i), which is consistent with Scherf et al.'s (2006) finding that ABR from high-frequency stimuli (clicks) correlate with ASSR thresholds for 2000 and 4000 Hz. The lack of correlation between electrophysiologic thresholds at 500 Hz (Fig. 3g) is consistent with the finding in Fig. 2 that s-ASSR, not tb-ABR, thresholds are more accurate estimates of low-frequency auditory threshold.

DISCUSSION

We found that narrow-band chirp evoked 40-Hz s-ASSR is more accurate than tb-ABR for estimating 500 Hz behavioral threshold in that a smaller correction factor was needed to estimate behavioral threshold with the 40-Hz s-ASSR threshold. This is in agreement with Kaf et al. (2014) who found that, in children with mild conductive hearing loss due to otitis media with effusion, 40-Hz s-ASSR thresholds at 500 Hz were within ~5 dB of behavioral thresholds and tb-ABR thresholds were within ~20 dB. Others have reported s-ASSR measurements to be more accurate than tb-ABR estimates of 500 Hz behavioral threshold, though our results are more precise because we used a bracketing method near threshold and did not interpolate threshold from the common use of a level series function (Van der Reijden et al., 2006). While an adequate number of equivalent response averages were essential for good s-ASSR performance, in that 2000 averages were not enough but 4000 averages were sufficient, the accuracy of tb-ABR did not improve with additional response averaging. Given additional research, these findings may influence the clinical decision making of clinicians in choosing s-ASSR over tb-ABR for certain populations.

Why did s-ASSR more accurately estimate 500 Hz behavioral threshold than tb-ABR?

Compared to s-ASSR, waveform morphology of tb-ABR from low-frequency stimuli is not good (Fig. 4). *The duration of single-auditory-nerve-fiber action potentials are much shorter than the duration of one cycle of a low-frequency tone* (Wang, 1979), *which is why it is commonly said that onset synchrony is poor at low frequencies* (e.g., Durrant and Ferraro, 1999; Laukli et al., 1988; Sininger and Abdala, 1996). Waveform morphology is better for s-ASSR because the response oscillates at a low-frequency that is equivalent to commonly

used modulation rates (e.g., 25 ms for the 40-Hz modulation used here). s-ASSR can be visually interpreted by clinicians, unlike most conventional ASSR data acquisition systems which rely on statistical analyses for response detection. While some may argue that the s-ASSR is too subjective as compared to automated ASSR, s-ASSR is not as readily influenced by noise as a-ASSR (John et al., 2004), making it a better clinical tool for hostile testing conditions.

Effects of additional response averaging

Additional response averaging to low-frequency stimuli improved the performance of s-ASSR, but not tb-ABR measurements. The Kalman-weighted filtering technique eliminates noisy responses, but there is still a need to use a number of responses greater than those commonly used in the clinic. Our s-ASSR estimates of 500 Hz threshold were lower for Group 2 (4000 averages) than Group 1 (2000 averages), which is consistent with others who demonstrated a benefit of additional response averaging (e.g., Lutz et al., 2008; Özdamar and Delgado, 1996). However, our tb-ABR estimates of 500 Hz threshold did not improve with a greater amount of response averages, showing that the effects of poor neural onset synchrony cannot be resolved. *The additional time for good s-ASSR measurements is negligible, compared to the potential impact of over-estimating low-frequency hearing loss with tb-ABR measurements, which could result in hearing aid over-amplification.*

Limitations

There are notable limitations to our study. *i)* The brainstem origins of the tb-ABR differ from the subcortical and/or cortical origins of the 40-Hz s-ASSR used here. Since our study required the use of tb-ABR measurements from awake participants, the 40-Hz s-ASSR was a natural comparative measure for our awake participants and for similar subjective interpretation of the response. Amplitudes of 40-Hz s-ASSR are largest in wakefulness than in sleep (Dobie and Wilson, 1998; Linden et al., 1985), unlike the 80-Hz s-ASSR which is usually measured in sleeping participants in order to mitigate brain and muscular artifact (Cohen et al., 1991; Van Maanen and Stapells, 2005). Thus, the research reported here was a necessary step toward the more challenging measurement of 80-Hz s-ASSR in awake participants. *ii)* We did not find correlations between electrophysiologic and behavioral thresholds, which is inconsistent with other reports; however, these reports used data from participants with varying degrees of hearing loss (e.g., Scherf et al., 2006; Stueve and O'Rourke, 2003; Tomlin et al., 2006; Van Maanen and Stapells, 2005). Our dataset was purposefully limited to cooperating adults with normal hearing to do the initial work on which to build ongoing research on hearing loss in children. We certainly anticipate that electrophysiologic and behavioral thresholds will correlate, when a greater range of thresholds are used, and that we will be able to determine if s-ASSR thresholds require a lower correction factor than tb-ABR for estimating low-frequency threshold in ears with hearing loss. *iii)* Our dataset shows no differences between male and female groups for tests that are *not* averaging dependent (i.e., behavioral and a-ASSR thresholds). Picton et al. (2009) have also previously reported no gender effects for a-ASSR. Nonetheless, the gender issue remains a limitation of the study, and additional research using s-ASSR in awake participants with hearing loss would further validate the findings of our study.

Clinical implications of sinusoidal ASSR in low-frequency hearing assessment

Objective measures of hearing are useful in children and those with special needs. Our findings with the Kalman-weighted filtering technique show that the s-ASSR can assess low-frequency hearing in awake participants. These results suggest that the common need for sedation could be reduced for objective assessment of hearing, but the origin of the s-ASSR limits its use to assess *cochlear* physiology. A new technique – the Auditory Nerve Overlapped Waveform – originates in the apical portion of the cochlear spiral and relates low-characteristic frequency single-auditory-nerve-fibers thresholds within 10–15 dB, which is the extent to which compound action potentials relate to high-frequency thresholds (Lichtenhan et al., 2013, 2014). Combining conventional and new techniques for low-frequency hearing assessment is a worthwhile endeavor. When frequency-specific measurements are needed after failing a hearing screening, we suggest combining one of these new techniques for low-frequency hearing with established measurements that work adequately only for high frequencies (above ~1 kHz) in the basal portion of the cochlea (e.g., compound action potentials or ABRs). Ultimately, improved assessment techniques should be used to better address the important low frequencies that are greatly underserved by audiological hearing aid fittings.

CONCLUSIONS

Kalman-weighted filtering and *in-situ* pre-amplification provide a technique to make measurements in awake and noisy participants – an advantage over conventional objective measurements that often require sedating children and special populations. Measurements of 40-Hz s-ASSR from narrow-band chirps require a smaller correction factor than tb-ABR for estimating low-frequency behavioral thresholds, and are equally optimal for estimating mid- to high-frequency behavioral thresholds. However, an adequate equivalent response averaging is essential, in that 2000 responses are not enough but 4000 are sufficient. The consequence of additional time needed for greater response averaging is negligible, compared to the benefit of accurately estimating low-frequency hearing thresholds for appropriate hearing aid programming for speech vowels and background noise. Based on our findings, we advocate for combining s-ASSR estimates of low-frequency hearing thresholds with tb-ABR or s-ASSR measures of high-frequency threshold until reliable behavioral thresholds can be obtained.

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Abbreviations

ASSR	auditory steady state response
s-ASSR	sinusoidal auditory steady state response

a-ASSR	automated auditory steady state response
ABR	auditory brainstem response
tb-ABR	tone-burst auditory brainstem response

References

- Bruhn, E. Unpublished doctoral project. University of Kansas Medical Center; 2012. Effects of subject activity on the auditory brainstem response measured with two different recording instruments.
- Chan FHY, Lam FK, Poon PWF, Qiu W. Detection of brainstem auditory evoked potential by adaptive filtering. *Med Biol Eng Comput.* 1995; 33(1):69–75. [PubMed: 7616785]
- Chertoff M, Lichtenhan J, Willis M. Click- and chirp-evoked human compound action potentials. *J Acoust Soc Am.* 2010; 127(5):2992–2996. [PubMed: 21117748]
- Cohen LT, Rickards FW, Clark GM. A comparison of steady-state evoked potentials to modulated tones in awake and sleeping humans. *J Acoust Soc Am.* 1991; 90(5):2467–2479. [PubMed: 1774415]
- Cone B, Norrix LW. Measuring the Advantage of Kalman-Weighted Averaging for Auditory Brainstem Response Hearing Evaluation in Infants. *Am J Audiol.* 2015:1–16. epub ahead of print. [PubMed: 25381440]
- Dobie RA, Wilson MJ. Low-level steady-state auditory evoked potentials: effects of rate and sedation on detectability. *J Acoust Soc Am.* 1998; 104(6):3482–3488. [PubMed: 9857507]
- Durrant, J.; Ferraro, J. Short-latency auditory evoked potentials: electrocochleography and auditory brainstem response. In: Musiek, F.; Rintelmann, W., editors. *Contemporary Perspectives in Hearing Assessment.* Needham Heights MA: Allyn & Bacon; 1999. p. 197-242.
- Elberling C, Don M. Auditory brainstem responses to a chirp stimulus designed from derived-band latencies in normal hearing subjects. *J Acoust Soc Am.* 2008; 124(5):3022–37. [PubMed: 19045789]
- Elberling C, Don M, Cebulla M, Stürzebecher E. Auditory steady-state responses to chirp stimuli based on cochlear traveling wave delay. *J Acoust Soc Am.* 2007; 122(5):2772–85. [PubMed: 18189568]
- Engelien A, Schulz M, Ross B, Arolt V, Pantev C. A combined functional in vivo measure for primary and secondary auditory cortices. *Hear Res.* 2000; 148(1):153–160. [PubMed: 10978832]
- Firsching R, Luther J, Eidelberg E, Brown WE, Story JL, Boop FA. 40 Hz—middle latency auditory evoked response in comatose patients. *Electroen Clin Neuro.* 1987; 67(3):213–216.
- Fogerty D, Kewley-Port D, Humes LE. The relative importance of consonant and vowel segments to the recognition of words and sentences: Effects of age and hearing loss. *J Acoust Soc Am.* 2012; 132(3):1667–1678. [PubMed: 22978895]
- Fogerty D, Humes LE. The role of vowel and consonant fundamental frequency, envelope, and temporal fine structure cues to the intelligibility of words and sentences. *J Acoust Soc Am.* 2012; 131:1490–1501. [PubMed: 22352519]
- Galambos R, Makeig S, Talmachoff PJ. A 40-Hz auditory potential recorded from the human scalp. *P Natl Acad Sci.* 1981; 78(4):2643–2647.
- Gorga MP, Kaminski JR, Beauchaine KA, Jesteadt W. Auditory brainstem responses to tone bursts in normally hearing subjects. *J Speech Hear Res.* 1988; 31(1):87. [PubMed: 3352259]
- Gorga MP, Neely ST, Bergman B, Beauchaine KL, Kaminski JR, Peters J, Jesteadt W. Otoacoustic emissions from normal hearing and hearing-impaired subjects: distortion product responses. *J Acoust Soc Am.* 1993; 93:2050–60. [PubMed: 8473617]
- Herdman AT, Lins O, Van Roon P, Stapells DR, Scherg M, Picton TW. Intracerebral sources of human auditory steady-state responses. *Brain Topogr.* 2002; 15(2):69–86. [PubMed: 12537303]
- Hyde ML. Newborn hearing screening programs: overview. *J Otolaryngol.* 2005; 34(2):S70. [PubMed: 16076420]

- Jerger J. Clinical experience with impedance audiometry. *Arch Otolaryngol Head Neck Surg.* 1970; 92(4):311.
- John MS, Brown DK, Muir PJ, Picton TW. Recording auditory steady-state responses in young infants. *Ear Hear.* 2004; 25(6):539–553. [PubMed: 15604915]
- Johnson, K. Unpublished doctoral project. University of Kansas Medical Center; 2012. Universal newborn hearing screening in the NICU population using new features of the Vivosonic Integrity ABR unit: assessing the correlation coefficient as a function of the number of sweeps collected.
- Kaf WA, Danesh AA. Air-conduction auditory steady-state response: comparison of interchannel recording using two modulation frequencies. *J Am Acad Audiol.* 2008; 19(9):696–707. [PubMed: 19418709]
- Kaf, WA.; Mohamed, ES.; Elshafiey, H. 40-Hz sinusoidal ASSR and TB-ABR thresholds in detecting mild conductive hearing loss in children with otitis media with effusion. Oral presentation at the HEAL 2014: Hearing Across the Lifespan Conference; Cernobbio, Lake Como, Italy. June 5–7, 2014; 2014.
- Korczak P, Smart J, Delgado R, M Strobel T, Bradford C. Auditory steady-state responses. *J Am Acad Audiol.* 2012; 23(3):146–170. [PubMed: 22436114]
- Kuwada S, Anderson JS, Batra R, Fitzpatrick DC, Teissier N, D'Angelo WR. Sources of the scalp-recorded amplitude-modulation following response. *J Am Acad Audiol.* 2002; 13(4):188–204. [PubMed: 12025895]
- Laukli E, Fjermedal O, Mair IW. Low-frequency auditory brainstem response threshold. *Scand Audiol.* 1988; 17:171–178. [PubMed: 3206183]
- Lichtenhan JT, Cooper NP, Guinan JJ. A new auditory threshold estimation technique for low frequencies: proof of concept. *Ear Hear.* 2013; 34(1):42. [PubMed: 22874644]
- Lichtenhan JT, Hartsock JJ, Gill RM, Guinan JJ Jr, Salt AN. The auditory nerve overlapped waveform (ANOW) originates in the cochlear apex. *J Assoc Res Otolaryngol.* 2014; 15(3):395–411. [PubMed: 24515339]
- Linden RD, Picton TW, Hamel G, Campbell KB. Human auditory steady-state evoked potentials during selective attention. *Electroenc Clin Neuro.* 1987; 66(2):145–159.
- Marcoux AM. Maturation of auditory function related to hearing threshold estimations using the auditory brainstem response during infancy. *Int J Pediatr Otorhinolaryngol.* 2011; 75(2):163–170. [PubMed: 21129787]
- Nozza RJ. Estimating the contribution of non-sensory factors to infant-adult differences in behavioral thresholds. *Hearing Res.* 1995; 91(1):72–78.
- Özdamar Ö, Delgado RE. Measurement of signal and noise characteristics in ongoing auditory brainstem response averaging. *Ann Biomed Eng.* 1996; 24(6):702–715. [PubMed: 8923990]
- Parry G, Hacking C, Bamford J, Day J. Minimal response levels for visual reinforcement audiometry in infants. *Int J Audiol.* 2003; 42(7):413–417. [PubMed: 14582637]
- Picton TW, Van Roon P, John MS. Multiple auditory steady state responses (80–101 Hz): effects of ear, gender, handedness, intensity and modulation rate. *Ear Hear.* 2009; 30(1):100–109. [PubMed: 19125032]
- Roeser, RJ.; Valente, M.; Hosford-Dunn, H. *Audiology: Diagnosis (Volume 1).* Thieme Publishers; 2007.
- Salt AN, Vora AR. Cochlear threshold assessment using tone-derived action potentials. *Audiol.* 1990; 29:135–145.
- Schmida MJ, Peterson HJ, Tharpe AM. Visual reinforcement audiometry using digital video disc and conventional reinforcers. *Am J Audiol.* 2003; 12(1):35. [PubMed: 12894866]
- Scherf F, Brox J, Wuyts FL, Van de Hyening PH. The ASSR: Clinical application in normal hearing & hearing-impaired infants & adults, comparison with the click-evoked ABR & pure tone audiometry. *Int J Audiol.* 2006; 45:281–286. [PubMed: 16717018]
- Sininger, YS. The use of auditory brainstem response in screening for hearing loss and audiometric threshold prediction. In: Burkard, RF.; Eggermont, JJ.; Don, M., editors. *Auditory Evoked Potentials: Basic Principles and Clinical Application.* Baltimore, MD: Lippincott Williams & Wilkins; 2007. p. 254-274.

- Sininger YS, Abdala C. Hearing threshold as measured by auditory brain stem response in human neonates. *Ear Hear.* 1996; 17:395–401. [PubMed: 8909887]
- Sokol J, Hyde M. Hearing screening. *Pediatr Rev.* 2002; 23(5):155–162. [PubMed: 11986491]
- Sokolov, Y.; Kurtz, I.; Steinman, A.; Long, G.; Sokolova, O. Integrity technology: enabling practical ABR. Vivosonic, Inc; 2006. Retrieved from vivosonic.com
- Sokolov, Y.; Kurtz, I.; Steinman, A.; Long, G.; Sokolova, O. Non-sedated ABR techniques. Presented at EHDI Conference; Dallas, TX. Vivosonic, Inc; 2009.
- Spoor, A.; Eggermont, JJ. Electrocochleography as a method for objective audiogram determination. In: Hirsch, SK.; Eldredge, DH.; Hirsch, IJ.; Silverman, SR., editors. *Hearing and Davis: Essays Honoring Hallowell Davis*. Saint Louis, MO: Washington University Press; 1976. p. 411–418.
- Spydell JD, Pattee G, Goldie WD. The 40 Hertz auditory event-related potential: normal values and effects of lesions. *Electroenc Clin Neuro.* 1985; 62(3):193–202.
- Stapells DR, Oates P. Estimation of the pure-tone audiogram by the auditory brainstem response: a review. *Audiol Neurotol.* 1997; 2(5):257–280.
- Stapells DR. Threshold estimation by the tone-evoked auditory brainstem response: a literature meta-analysis. *J Speech Lang Pathol Audiol.* 2000; 24(2):74–83.
- Steinmann I, Gutschalk A. Potential fMRI correlates of 40-Hz phase locking in primary auditory cortex, thalamus and midbrain. *Neuroimage.* 2011; 54(1):495–504. [PubMed: 20688174]
- Stueve MP, O'Rourke C. Estimation of hearing loss in children: comparison of auditory steady-state response, auditory brainstem response, and behavioral test methods. *Am J Audiol.* 2003; 12:125–136. [PubMed: 14964328]
- Tomlin D, Rance G, Graydon K, Tsialios I. A comparison of 40 Hz auditory steady-state response (ASSR) and cortical auditory evoked potential (CAEP) thresholds in awake adult subjects. *Int J Audiol.* 2006; 45(10):580–588. [PubMed: 17062499]
- Tlumak A, Rubinstein E, Durrant J. Meta-analysis of variables that affect accuracy of threshold estimation via measurement of the auditory steady-state response (ASSR). *Int J Audiol.* 2007; 46(11):692–710. [PubMed: 17978952]
- Van der Reijden C, Mens LHM, Snik AFM. Frequency-specific objective audiometry: tone-evoked brainstem responses and steady-state responses to 40 Hz and 90 Hz amplitude modulated stimuli. *Int J Audiol.* 2006; 45:40–45. [PubMed: 16562563]
- Van Maanen A, Stapells DR. Comparison of multiple auditory steady-state responses (80 versus 40 Hz) and slow cortical potentials for threshold estimation in hearing-impaired adults. *Int J Audiol.* 2005; 44(11):613–624. [PubMed: 16379489]
- Wang, B. Doctoral dissertation. Massachusetts Institute of Technology; 1979. The relation between the compound action potential and unit discharges in the auditory nerve.
- Westhuizen, C. Unpublished doctoral dissertation. University of Pretoria; Gauteng, South Africa: 2010. The clinical utility of the Vivosonic Integrity auditory brainstem response system in children with cerebral palsy.
- Wheeler, JK. Doctoral dissertation. James Madison University; 2011. The effect of Kalman-weighted filtering and in-situ pre-amplification on the accuracy and efficiency of ABR threshold estimation.
- Wiegers, JS. Unpublished doctoral thesis. Ohio State University; 2013. Utility of Vivosonic Integrity ABR system as a hearing screening device for children who are difficult to test.

Figure 1.

Average a-ASSR thresholds were greater than behavioral thresholds for all frequencies for both Group 1 (female) and Group 2 (male). Error bars are estimates of ± 1 standard deviation. Average a-ASSR thresholds were indistinguishable between Group 1 & 2 for all stimulus frequencies. The lack of difference in behavioral thresholds, as well as a-ASSR thresholds, between Groups 1 & 2 suggest that s-ASSR effects reported below are not due to gender differences but are instead due to differences in the number of equivalent responses averages between groups.

Figure 2.

tb-ABR and s-ASSR thresholds were higher than behavioral thresholds for all stimulus frequencies. Brackets with asterisks indicate $p < .001$ for post-hoc t -tests for comparison between the two electrophysiological tests (see Table 2). Group 1 tb-ABR thresholds were significantly lower than s-ASSR thresholds for 4000 Hz only. Group 2 tb-ABR and s-ASSR thresholds were indistinguishable for 2000 and 4000 Hz and tb-ABR thresholds were significantly higher than s-ASSR thresholds for 500 Hz. Error bars are estimates of ± 1 standard deviation. The smaller difference between behavioral and electrophysiologic thresholds demonstrates that s-ASSR is more accurate than tb-ABR for estimating low-frequency auditory threshold.

Figure 3.

Top row: tb-ABR thresholds as a function of behavioral thresholds for 500 Hz (Fig. 3a), 2000 Hz (Fig. 3b), and 4000 Hz (Fig. 3c). No significant correlations existed for either Group 1 or 2. *Middle row:* s-ASSR thresholds as a function of 500 Hz (Fig. 3d), 2000 Hz (Fig. 3e), and 4000 Hz behavioral thresholds (Fig. 3f). No significant correlations exist for either Group 1 or 2. *Bottom row:* s-ASSR thresholds as a function of tb-ABR thresholds for 500 Hz (Fig. 3g), 2000 Hz (Fig. 3h), and 4000 Hz (Fig. 3i). While no significant correlations exist for Group 1 (r values in *black*), s-ASSR threshold correlated significantly with tb-ABR thresholds for 2000 and 4000 Hz for Group 2 (r values in *gray*) but not for 500 Hz.

Figure 4. Example tb-ABR (*bottom panel*) and 40 Hz s-ASSR waveforms from Subject #3 in response to 500 Hz stimuli presented at 40 dB nHL. The peaks of s-ASSR (*top panel*) waveforms are separated by the period of the modulation frequency.

Table 1

Repeated Measures Analysis of Variance (ANOVA) results for main effects and interactions for test type (behavioral, tb-ABR, and s-ASSR thresholds) and group (Group 1 and Group 2) performed separately for stimulus frequencies 500, 2000, and 4000 Hz. η^2 = Partial Eta Squared

Frequencies	Variables	F	df	p	η^2
500 Hz	test type	149.12	2, 54	<.001	0.85
	group	12.17	1	<.001	0.31
	test type*group	10.97	2, 54	<.001	0.29
2000 Hz	test type	69.23	2, 54	<.001	0.72
	group	28.34	1	<.001	0.51
	test type*group	12.54	2, 54	<.001	0.32
4000 Hz	test type	56.89	2, 54	<.001	0.68
	group	28.34	1	<.001	0.51
	test type*group	12.54	2, 54	<.001	0.32

Results from post-hoc paired samples *t*-tests performed separately for stimulus frequencies 500, 2000, and 4000 Hz. For both Group 2 and Group 1, tb-ABR and s-ASSR thresholds were significantly higher (worse) than behavioral thresholds. *d* = effect size (Cohen's *d*)

Table 2

Frequencies	Test Types	Group 1			Group 2		
		<i>t</i> (14)	<i>p</i>	<i>d</i>	<i>t</i> (13)	<i>p</i>	<i>d</i>
500 Hz	Behavioral to tb-ABR	-11.37	<.001	4.71	-19.57	<.001	5.75
	Behavioral to s-ASSR	-10.86	<.001	4.07	-8.8	<.001	3.33
	tb-ABR to s-ASSR	-0.79	.444	0.00	7.35	<.001	2.59
2000 Hz	Behavioral to tb-ABR	-9.87	<.001	3.81	-5.72	<.001	2.12
	Behavioral to s-ASSR	-8.28	<.001	2.91	-5.21	<.001	1.57
	tb-ABR to s-ASSR	-1.69	.114	0.55	1.15	.272	0.25
4000 Hz	Behavioral to tb-ABR	-8.15	<.001	2.75	-3.57	.003	1.32
	Behavioral to s-ASSR	-9.06	<.001	3.68	-3.87	.002	1.26
	tb-ABR to s-ASSR	-4.22	.001	1.36	-0.86	.405	0.21