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Comparison of Auditory Steady-State Response and Auditory Brainstem Response Thresholds in Children

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Abstract

Recently, auditory steady-state responses (ASSRs) have been proposed as an alternative to the auditory brainstem response (ABR) for threshold estimation. The goal of this study was to investigate the degree to which ASSR thresholds correlate with ABR thresholds for a group of sedated children with a range of hearing losses. Thirty-two children from the University of Iowa Hospitals and Clinics ranging in age from 2 months to 3 years and presenting with a range of ABR thresholds participated. Strong correlations were found between the 2000-Hz ASSR thresholds and click ABR thresholds (r = .96), the average of the 2000- and 4000-Hz ASSR thresholds and click ABR thresholds (r = .97), and the 500-Hz ASSR and 500-Hz toneburst ABR thresholds (r = .86). Additionally, it was possible to measure ASSR thresholds for several children with hearing loss that was great enough to result in no ABR at the limits of the equipment. The results of this study indicate that the ASSR may provide a reasonable alternative to the ABR for estimating audiometric thresholds in very young children.

Key Words: Auditory brainstem response, auditory evoked responses, auditory steady-state responses

Abbreviations: ABR = auditory brainstem response; ASSR = auditory steady-state response

Sumario

Recientemente, se ha propuesto el uso de las respuestas auditivas de estado-estable (ASSR: auditory steady-state responses) como una alternativa a las respuestas auditivas del tallo cerebral (ABR: auditory brainstem responses) para la estimación de umbrales. La meta de este estudio fue la de investigar el grado de correlación entre los umbrales de las ASSR y los umbrales de las ABR para un grupo de niños sedados presentando un rango de hipoacusias. Participaron treinta y dos niños de los Hospitales y Clínicas de la Universidad de Iowa, en edades entre los 2 meses y los 3 años, y con una variedad de umbrales para ABR. Se encontraron correlaciones fuertes entre el umbral de ASSR a 2000 Hz y los umbrales con click para ABR (r = .96), entre el promedio de umbrales de ASSR para 2000 Hz y 4000 Hz y los umbrales con click para ABR (r = .97), y entre las ASSR a 500 Hz y los umbrales de ABR para bursts tonales de 500 Hz (r = .86). Además, fue posible medir umbrales de ASSR en varios niños cuyas pérdidas auditivas eran tan grandes como para no mostrar resultados de ABR a la intensidad límite del equipo. Los resultados de este estudio indican que las ASSR pueden aportar una alternativa razonable al ABR para estimar umbrales audiométricos en niños muy jóvenes.

Palabras Clave: Respuesta auditiva del tallo cerebral, respuestas auditivas evocadas, respuestas auditivas de estado-estable

Abreviaturas: ABR = respuestas auditivas del tallo cerebral; ASSR = respuestas auditivas de estado-estable

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Recently, both the National Institutes of Health (National Institutes of Health, 1993) and the American Academy of Pediatrics (American Academy of Pediatrics, 1999) issued statements calling for universal hearing screening of all newborns. The importance of universal hearing screening is underscored by the work of Yoshinaga-Itano and colleagues (1998, 2000) and Moeller (2000), who demonstrated that hearing-impaired children who receive intervention during the first 6 to 12 months of life are able to develop better speech and language skills than children for whom intervention is delayed. However, the process of fitting a hearing aid or determining if a specific child is a cochlear implant candidate requires knowledge of that child's residual hearing abilities. For many children, it may be possible to use age-appropriate behavioral techniques to estimate hearing thresholds for audiometric frequencies from 250 to 4000 Hz. For others, however, that is not the case. For those children, evoked potential estimates of audiometric threshold may be the only information about the child's hearing status that is available at the time these critical decisions need to be made.

The auditory brainstem response (ABR) is a far-field evoked potential that is used almost universally to estimate auditory sensitivity in children too young to be tested using standard behavioral methods. The ABR to click stimuli is probably the most commonly used clinically. Although the abrupt onset of the click stimulus is ideal for generating the ABR, the drawback is that the resulting frequency spectrum is broad. Additionally, behavioral thresholds have been shown to increase as the duration of an acoustic stimulus decreases (Gorga et al, 1984). Therefore, when short-duration stimuli such as clicks are used, higher input voltages to the earphones are needed to produce threshold-level responses. Transducer-dependent input voltage maximums effectively limit the maximum output levels, making it difficult to distinguish between severe and profound losses using the type of stimuli and transducers typically used to record the ABR. Studies have, in fact, shown that the click ABR does a relatively poor job of differentiating hearing losses in the severe range from those in the profound range (Brookhouser et al, 1990; Rance et al, 1998; Schoonhoven et al, 2000).

ABR to brief tones can be used to obtain more frequency-specific threshold information than is available from the click ABR. A recent meta-analysis of the toneburst ABR literature by Stapells (2000) has shown that across studies, tone-ABR thresholds have been found to be between 10 and 20 dB nHL in normal-hearing individuals and are generally within 15 dB of behavioral threshold for hearing-impaired individuals (+5 to 15 dB for adults, ±10 dB for infants and young children). However, some studies have questioned the frequency specificity and reliability of threshold estimation with low-frequency tone-evoked ABR (Hayes and Jerger, 1982; Gorga et al, 1988; Laukli et al, 1988). In addition, toneburst ABR waveforms, especially to low-frequency stimuli, tend to be less distinct and more difficult to identify than the click ABR. Output limitations are also a concern with toneburst stimuli, particularly for low-frequency tonebursts for which thresholds are elevated relative to behavioral threshold. These concerns may limit the implementation of toneburst ABR protocols in many clinics.

The auditory steady-state response (ASSR) is an alternative evoked potential technique that uses continuous rather than transient stimuli to elicit a response from the auditory system. Steady-state responses were first reported in the literature decades ago (Galambos et al, 1981; Stapells et al, 1984). Kuwada et al (1986) published one of the first papers describing steady-state responses evoked using amplitude-modulated sinusoidal stimuli. This study, and many of the studies that followed, used relatively low rates of amplitude modulation (approximately 40 Hz) to evoke the response (Milford and Birchall, 1989; Griffiths and Chambers, 1991; Aoyagi et al, 1993). Despite initial enthusiasm surrounding this research, it soon became clear that the ASSR, evoked using low-modulation frequencies, was adversely affected by sleep and sedation and was not able to be recorded reliably in very young children (Stapells et al, 1988; Cohen et al, 1991; Aoyagi et al, 1993; Dobie and Wilson, 1998). More recent research has shown that if modulation frequencies between approximately 70 and 100 Hz are used, the resulting response, although smaller in amplitude than the response evoked using lower-modulation frequencies, can be recorded reliably in sedated infants (Aoyagi et al, 1994a; Rickards et al, 1994; Rance et al, 1995; Lins et al, 1996).

Several investigators have reported finding significant correlations between high-rate ASSR thresholds and behavioral audiometric thresholds for individuals with a range of hearing losses (Aoyagi et al, 1994b; Levi et al, 1995; Rance et al, 1995, Lins et al, 1996; Picton et al, 1998). Although these results appear promising, it is difficult to make definitive conclusions by comparing across studies because the parameters used for data collection and analysis varied widely. In some studies, the ASSR was evoked using a single-frequency stimulus (Aoyagi et al, 1994a, b; Levi et al, 1995; Rance et al, 1995), whereas in other studies, the ASSR was evoked using multiple-frequency stimuli presented simultaneously (Lins et al, 1996; Picton et al, 1998). Many studies used adults or older children rather than infants to evaluate the efficacy of the ASSR as a threshold estimation tool (Aoyagi et al, 1994b, 1996, 1999; Lins and Picton, 1995; Lins et al, 1996; Picton et al, 1998). Some studies used simple amplitude modulation (Aoyagi et al, 1994b; Levi et al, 1995; Lins et al, 1996; Picton et al, 1998), whereas others used a combination of both amplitude and frequency modulation (Rickards et al, 1994; Rance et al, 1995). To date, no consensus has been reached regarding the optimal protocol for stimulation, recording, and analysis of the ASSR. This fact, coupled with the fact that instrumentation needed to record the ASSR is not yet available in the United States from a commercial manufacturer of evoked potential equipment, has delayed acceptance of the ASSR into clinical practice in the United States. The potential advantages of ASSR that come from continuous rather than transient stimuli, including potentially better frequency specificity and the ability to obtain higher output levels, warrant further investigation in the pediatric population. In addition, the objective nature of response determination makes ASSR attractive in a clinical setting.

The purpose of this study was to compare ASSR thresholds and ABR thresholds in a group of infants with a range of hearing impairments using protocols that may be feasible in routine clinical practice. The equipment used in this study to record the ASSR was manufactured by ERA Systems, Ltd. This device is a prototype for the Audera from Nicolet Biomedical Instruments that is scheduled for beta testing in early 2002. The children participating in this study were those being seen for threshold evaluation using evoked potential techniques at the University of Iowa Hospitals and Clinics between 2000 and 2001. Because reliable audiometric information was not available from these children at the time they were tested, the goal of the study was to determine if threshold estimates obtained using the ASSR were comparable with those obtained using the ABR as recorded in routine clinical practice.

METHOD

Subjects

Thirty-two children (23 males, 9 females) seen at the University of Iowa Hospitals and Clinics between January 2000 and June 2001 were included in this study. Ages of the subjects ranged from 0 years, 2 months to 3 years, 3 months at the time of testing. Children scheduled for a sedated ABR evaluation during that time were recruited as subjects, and informed consent was obtained from a parent/guardian. All subjects had normal middle ear function as determined by an otoscopic examination by the attending physician and/or tympanometry. Although the neurologic integrity of the subjects was not assessed, no subjects were known to have gross developmental disorders, and ABR morphology, when recorded, was also normal.

General Procedures

Subjects were sedated with chloral hydrate (50 mg/kg, administered orally) and were monitored for oxygen saturation, respiratory rate, and heart rate throughout the procedure by a nurse from the otolaryngology clinic. Testing took place in the audiology clinic inside a double-walled sound-treated booth. ABR testing was always completed first. Initially, click-evoked ABR thresholds were recorded bilaterally. For most children, ABR thresholds were then recorded for both ears using 500-Hz toneburst stimuli. ASSR testing began after the ABR testing was completed. ASSR testing was typically completed at 2000 Hz and 500 Hz in both ears. If time permitted and the child was still sleeping, ASSR testing at 4000 Hz followed. In many cases, the child awoke, and testing was terminated before this protocol had been completed. Data were ultimately obtained for 57 ears of the 32 children. Total testing time was generally approximately 1 hour.

Stimulation and Recording Parameters

Auditory Brainstem Response

The ABR was recorded using both ipsilateral and contralateral electrode montages with high forehead positive, the mastoids negative, and the ground electrode positioned on the low forehead. The same electrodes were used for both ABR and ASSR testing. Electrode impedance values were all ≤ 5 kohms and were within 1.5 kohms of each other.

The stimuli used to elicit the ABR were generated by the Biologic Navigator evoked potential system and were presented via insert earphones (Etymotic ER-3A). Click stimuli were 100 μsec in duration and were presented at a rate of 39.7/sec with alternating polarity. Toneburst stimuli were 500-Hz tones, linearly gated with a two-cycle rise–fall time and a one-cycle plateau. Tone bursts were presented at a rate of 27.7/sec. Figure 1 shows the frequency spectra of the ABR stimuli used in this study.

Click and toneburst ABRs were recorded using filter settings of 100 to 3000 Hz (6 dB/octave) and amplified using a gain of 100,000. Time windows of 15 msec were used to record the click-evoked ABRs. Time windows of 25 msec were used to record toneburst-evoked ABRs. At each presentation level, a minimum of 1500 sweeps was averaged. Step sizes of 10 dB were used for presentation levels that were clearly suprathreshold. The step size was reduced to 5 dB near threshold, and a minimum of two replications of the ABR was recorded at stimulation levels near threshold. Artifact rejection was used to minimize contamination of the ABR by myogenic activity. Threshold was defined as the lowest level that resulted in a replicable ABR wave V response as determined by two judges experienced with ABR recordings.

Stimulation level was calibrated in dB nHL. This calibration factor was determined experimentally by asking a set of 10 listeners with audiometrically normal hearing to indicate the lowest level at which the click and 500-Hz toneburst stimulus were audible. ABR thresholds were then obtained on these normal-hearing listeners using the stimulation and recording protocols outlined above. Mean click-evoked ABR thresholds were recorded for this group of normal-hearing listeners at 10 dB nHL. The mean 500-Hz toneburst ABR threshold recorded using these parameters was 40 dB nHL. The maximum stimulation level available with the Biologic system was 90 dB nHL for click stimuli and 85 dB nHL for the 500-Hz toneburst stimuli.

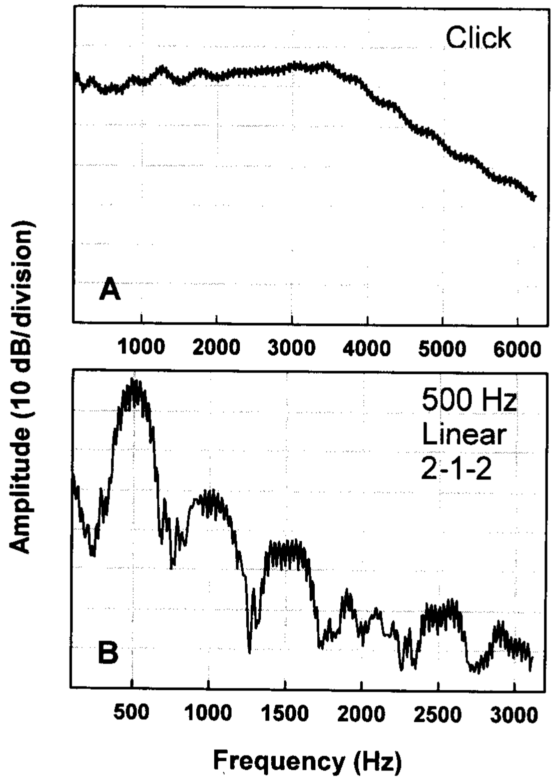

Figure 1 Frequency spectra for the auditory brainstem response stimuli used in this study presented through Etymotic ER-3A headphones at 90 dB nHL. *A* shows the spectra of the 100-μsec click. *B* displays the 500-Hz tone burst (linear gating, 2-1-2 cycle duration).

Auditory Steady-State Response

ASSRs were recorded using the ERA Systems, Ltd. device developed in Melbourne, Australia. Recently, Nicolet Biomedical, Inc. purchased this technology from ERA Systems, and this device has served as a prototype for the Audera device, which is currently undergoing premarket testing. The Audera and the ERA Systems devices use similar stimulation and recording paradigms to measure the ASSR.

The stimuli used to evoke the ASSR consisted of carrier frequencies of 500, 2000, and 4000 Hz that were 100 percent amplitude modulated and 10 percent frequency modulated at modulation frequencies of 74, 88, and 95 Hz, respectively. These stimuli were presented individually to the patient via Etymotic ER-3A insert earphones. Figure 2 shows the acoustic spectra of the amplitude-modulated stimuli used to evoke the ASSR.

The same recording electrodes used for ABR testing were used to record the ASSR. The high forehead electrode was positive, the ipsilateral mastoid was negative, and the contralateral mastoid was used as ground.

The ERA Systems, Ltd. device amplifies and bandpass filters electroencephalographic (EEG) activity from 3 to 5000 Hz. A 16-bit A/D converter with a sampling rate of 44.1 kHz is

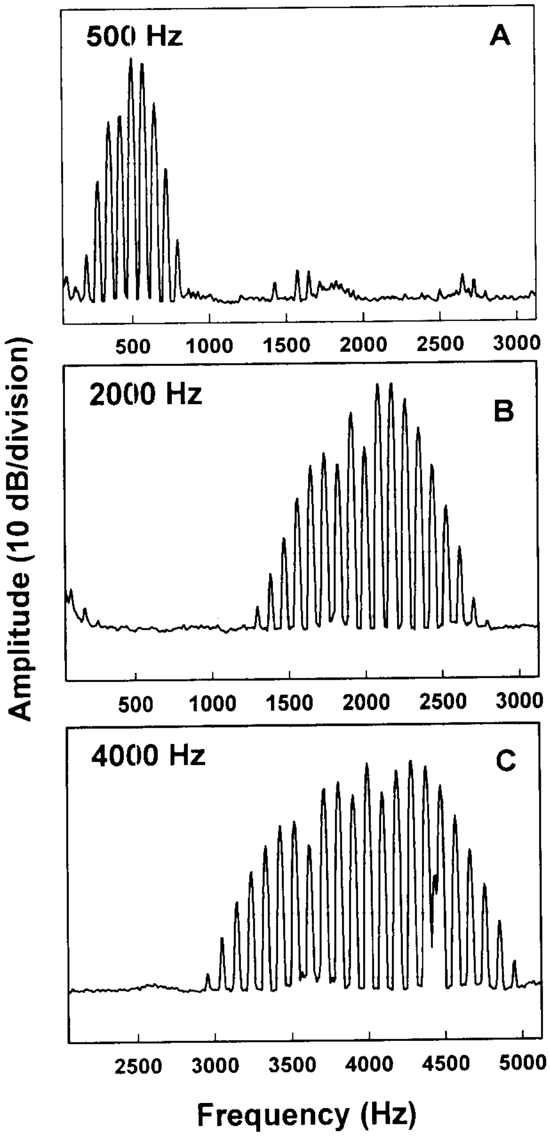

Figure 2 Frequency spectra for the auditory steady-state response stimuli presented through Etymotic ER-3A headphones at 70 dB HL. *A, B,* and *C* show the spectra of the 500-, 2000-, and 4000-Hz stimuli, respectively. The stimuli are 100 percent amplitude modulated and 10 percent frequency modulated at the rates of 74, 88, and 95 Hz, respectively. Note the change in the frequency scale for panel *C*.

used to digitize the incoming signal. The ERA device averages the ongoing EEG activity and computes the phase coherence of the spectral component of the response at the modulation frequency. Online statistical analysis is used to determine the probability that the observed response is owing to chance. Between 16 and 64 sweeps were analyzed during each recording, with testing terminated when the phase coherence reached statistical significance or at 64 sweeps if significance is not reached. The significance level was set in the software to a false-positive rate of 1 in 33, or a probability of 0.03. ASSR threshold estimation was conducted using 10-dB steps in an ascending series. Near threshold, two to three replications were recorded for each stimulation level. To compare with ABR thresholds that were obtained using 5-dB steps, ASSR threshold was interpolated between the lowest level that met significance criteria and a nonsignificant result 10 dB below.

The level of stimulation used for ASSR testing was calibrated using a Quest Model 1700 sound level meter equipped with a 1-inch B & K microphone and a B & K DB 0138 coupler. Signal levels in dB SPL were measured and converted to dB HL using ANSI S3.6-1996 corrections for the Etymotic ER-3A earphones.

RESULTS

Click ABR testing was completed on 57 ears of 32 children. Of those 57 ears, 31 had no response to clicks at the limits of the equipment. ASSR testing at 2000 Hz was completed on all 57 ears, with 13 of those ears having no response at the limits of the equipment. On 53 ears, 500-Hz toneburst ABR and 500-Hz ASSRs were completed. Thirty of those ears had no response to the 500-Hz tone burst at the limits of the equipment, whereas 20 had no response to the ASSR. All ears that had a click ABR also had a response to the 2000-Hz ASSR. Two ears had a click ABR and a 2000-Hz ASSR but no response ASSR at 4000 Hz. There were no cases at 500 Hz for which a response was obtained to the ABR stimulus but not to the ASSR.

Figure 3 show a series of representative ABR waveforms. The left panel of Figure 3

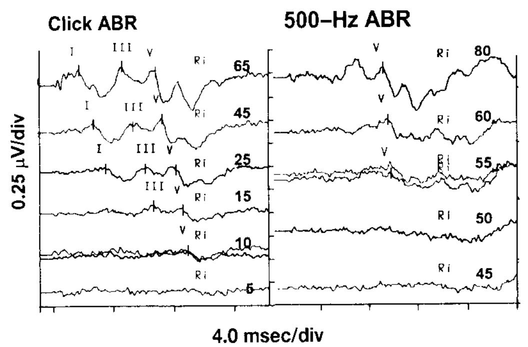

Figure 3 Representative auditory brainstem response (ABR) waveforms from two subjects. The left panel shows a click ABR series from subject NV. Numbers on the right side of the waveforms are stimulus level in dB nHL. The threshold for this subject was determined to be 10 dB nHL. The right panel shows the 500-Hz ABR from subject AC, whose threshold was 55 dB nHL.

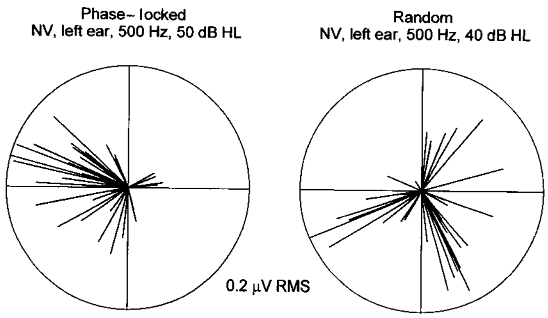

Figure 4 Representative auditory steady-state response results for one subject (NV) at two different levels. The *left panel* shows a significant phase-locked response at 50 dB HL at 500 Hz. Note the clustering of the vectors within one quadrant. The *right panel* shows a random, non–phase-locked result from the same subject at 500 Hz at 40 dB HL. In this example, the vectors are distributed randomly about the circle.

shows responses recorded using click stimuli. Wave V is marked on each waveform. In this example, the visual detection threshold was determined to be 10 dB nHL. The right panel of Figure 3 shows ABR responses obtained from a different subject using 500-Hz toneburst stimuli. Wave V is marked, and threshold was judged to be 55 dB nHL.

The ASSR is not analyzed in the time domain. Figure 4 shows the display from the ERA Systems device. This is a polar plot showing the amplitude and relative phase of the spectral component equal to the modulation frequency. If the subject hears the stimulus, as illustrated in the left panel of Figure 4, the vectors on the polar plot will be clustered together, indicating that the response has significant phase coherence. If the subject does not hear the stimulus, as illustrated in the right panel of Figure 4, the individual vectors on this plot will be recorded at random phase relative to each other.

Figure 5 shows the relationship between ABR and ASSR thresholds for children who participated in this study. Panels A and B compare thresholds obtained with the click ABR to the 2000-Hz ASSR and the 2000- and 4000-Hz average ASSR, respectively. Points plotted in the gray areas indicate that no response was obtained at the limits of the equipment for that evoked potential. It is important to note that a large proportion of ears (31 of 57) had no response to clicks at 90 dB nHL; therefore, only 26 ears are represented in the regression equation (dotted line) in panel A. These data indicate that there is a strong, significant correlation between ASSR thresholds at 2000 Hz and click

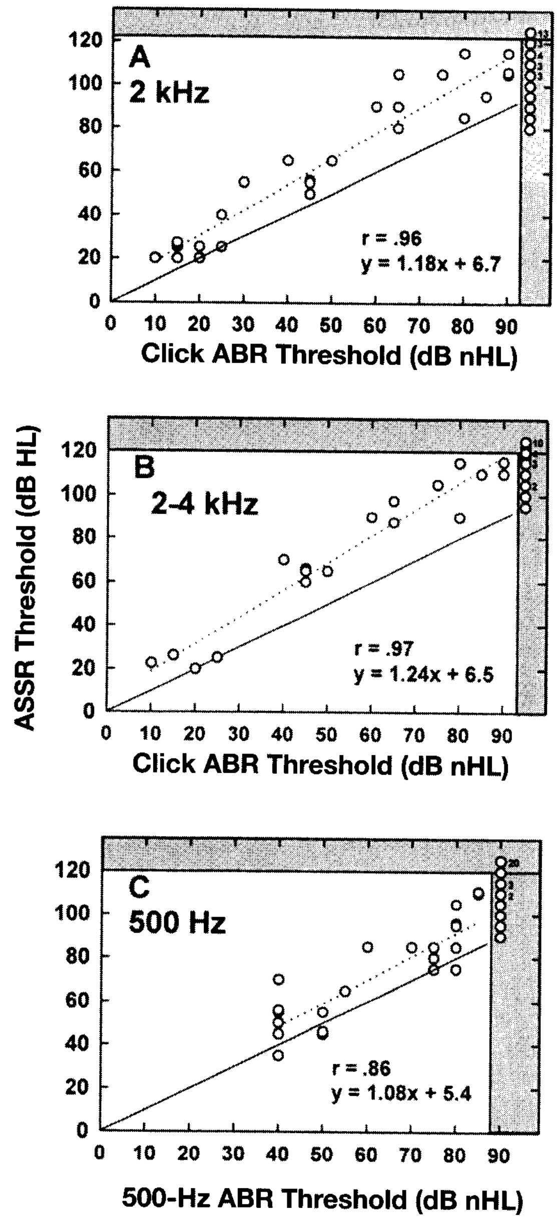

Figure 5 Scatter plots representing the relationship between auditory steady-state response (ASSR) thresholds in dB HL and auditory brainstem response (ABR) thresholds in dB nHL. Overlapping data points are represented by *offset symbols* (± 1 dB) or are noted by *the number of data points* included to the right of the symbol. The *gray areas* of each panel represent no response at the limits of the equipment. Subjects with no response at the maximum were arbitrarily assigned thresholds 5 dB above the limit for both ABR and ASSR. These no-response data points are not included in the regression analysis. The *dotted line* represents the regression line for each panel, whereas the *solid line* represents the point at which the two values are equal. Correlation coefficients and regression equations are given in the lower right of each panel. *A* displays the relationship between the 2000-Hz ASSR and the click ABR thresholds. *B* depicts the comparison between the 2000- to 4000-Hz average threshold for ASSR versus the click ABR threshold. *C* shows the relationship between the 500-Hz ASSR and the 500-Hz toneburst ABR thresholds.

ABR thresholds (r = .96). A similar correlation is found between the average of the 2000- and 4000-Hz ASSR thresholds and the click-evoked ABR threshold (r = .97), although there are fewer datum points (n = 18) in this figure owing to the fact that 4000-Hz thresholds were not obtained in all subjects.

Panel C of Figure 5 shows the relationship between 500-Hz toneburst ABR thresholds and the ASSR thresholds recorded using a 500-Hz carrier tone. Twenty-three ears with toneburst ABR responses are included in the regression, whereas the 30 ears with no response to toneburst ABR are not included but are shown in the gray area of the graph. Although the correlation between ASSR and ABR thresholds is not as strong as that observed between click ABR thresholds and high-frequency ASSR thresholds, the correlation is still significant and strong (r = .86).

DISCUSSION

The purpose of this study was to compare click and 500-Hz ABR thresholds to ASSR thresholds at 500, 2000, and 4000 Hz in infants and young children. The results of this study show that these two measures were found to have a strong positive relationship, with correlation coefficients ranging between .97 for the click ABR and the 2000- to 4000-Hz average ASSR thresholds to .86 for the 500-Hz ABR and ASSR.

Limited data exist directly comparing ABR and ASSR thresholds in hearing-impaired subjects. Johnson and Brown (unpublished data currently in review process) tested a small group of adults (N = 11) with a range of hearing losses and compared toneburst ABR thresholds with ASSR thresholds. A strong correlation (r = .91) between ABR and ASSR thresholds was obtained when the results collected at 500, 1000, and 2000 Hz were combined. The results of the present study agree well with these results and suggest that the ASSR may make a reasonable alternative to the ABR for threshold estimation in sedated infants. In studies that have compared the two types of physiologic thresholds to behavioral thresholds, the correlations between behavioral thresholds and ASSR were similar to the correlations to ABR (Aoyagi et al, 1994b, 1996, 1999). In the study with the largest data set, Aoyagi and colleagues (1999) compared behavioral thresholds to 1000-Hz toneburst ABR thresholds and to 1000-Hz ASSR thresholds for a group of 125 children ranging in age from 3 to 15 years. The correlation coefficient for ASSR to behavioral thresholds (r = .863, n = 169) was higher than that for ABR (r = .828, n = 93), although the difference was not significant. The thresholds for the two types of evoked potential thresholds were not directly compared.

The population for whom ASSR threshold estimation procedures may prove particularly beneficial is children with severe to profound hearing losses. In this study, we report data from 31 ears for which no click ABR was recorded at the maximum stimulation levels. Fifty-eight percent of these ears had measurable ASSR thresholds at 2000 Hz. At 500 Hz, 33 percent of the 30 ears that had no response at the limits of the ABR equipment had measurable ASSR thresholds. There were only 2 cases of ears for which an ABR response was judged to be present (both within 5 dB of the maximum stimulation level) with no response to ASSR in the high frequencies. Both of these cases had no response to ASSR at 4000 Hz but did have a response at 2000 Hz at least 15 dB below the maximum stimulation level. The 2000- to 4000-Hz average for these two subjects was calculated assuming an arbitrary threshold value of 125 dB HL at 4000 Hz; therefore, they are included in the regression analysis in Figure 5. There were no cases at 500 Hz for whom a response was obtained to the ABR stimulus but not to the ASSR.

These findings of a potential advantage of ASSR over ABR for severe to profound losses are consistent with the results of previously reported studies (Rance et al, 1995, 1998, 2001). These studies have shown that the error in prediction of hearing loss decreases with increasing degree of loss. Rance and colleagues (2001) found that the discrepancy between ASSR and behavioral thresholds was 5 dB or less for infants with severe to profound hearing loss. Rance and colleagues (1998) also found that no response to ASSR at maximum presentation levels strongly indicated profound or total hearing loss in a study of 108 infants and young children. Of the absent ASSR responses in the Rance and colleagues (1998) study, 99.5 percent corresponded to behavioral thresholds within 10 dB of the maximum ASSR level. This evidence indicates that absent ASSR implies no usable hearing at that frequency. This is not true of ABR, for which evidence has shown that absent click ABR does not rule out useful residual hearing (Brookhouser et al, 1990; Rance et al, 1998; Schoonhoven et al, 2000).

The test time for the ASSR protocol used in this study was generally longer than for the

ABR. However, the fact that the ASSR was always completed last, when subjects tended to be noisier, may have contributed to the increased test time. Also, the prototype device used for ASSR did not have the capability for artifact rejection or the presentation of multiple-stimulus frequencies either in the same ear or to both ears simultaneously. Future versions of the device that allow for these features will most likely decrease test time significantly.

The behavioral thresholds of the subjects in the current study were not known. Therefore, the relative accuracy of the threshold estimations based on the two evoked potentials cannot be compared. However, the results of this study indicate that ASSR thresholds are highly correlated with ABR results in sedated infants. These results are to be expected and are reassuring given that ABR and ASSR are likely generated from many of the same anatomic structures. However, ASSR thresholds may provide additional information for the characterization of severe to profound hearing loss. These results support the use of ASSR as an alternative to ABR for threshold assessment in infants.

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