The Auditory Steady-State Response: Clinical Observations and Applications in Infants and Children

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Abstract

Two studies illustrate the use of the auditory steady-state response (ASSR) in the pediatric clinical audiology setting. A protocol for estimating bone-conduction thresholds from ASSR was developed. Bone-conducted narrow-band noise was used to mask the ASSR for a 1.0-kHz modulated tone. The amount of bone-conducted noise needed to mask the ASSR may distinguish between infants and children with conductive hearing losses and those with sensory losses. The amount of bone-conducted noise may also be used to estimate bone-conduction thresholds; however, the accuracy of this technique needs verification with behavioral methods to determine thresholds for bone-conducted pure tones in infants. When ASSR tests are used as part of the diagnostic evaluation for infants and children at risk for hearing loss, the results yield information about the audiometric contour and residual hearing, which aid in treatment and habilitation decisions.

Key Words: Auditory evoked potentials, auditory threshold, infant

Abbreviations: AC = air conducton; AM = amplitude modulated; ABR = auditory brainstem response; ASSR = auditory steady-state response; BC = bone conduction; c-ABR = click-evoked ABR; DPOAE = distortion-product otoacoustic emission; EM = effective masking; EOAE = evoked otoacoustic emission; MF = modulation frequency; NBN = narrow-band noise; PC² = phase coherence squared; RCH = Royal Children's Hospital; REFTL = reference equivalent force threshold level; SAL = sensorineural acuity level; tb-ABR = toneburst-evoked ABR; TEOAE = transient evoked otoacoustic emission; VIHSP = Victorian Infant Hearing Screening Program

Sumario

Dos estudios ilustran el uso de las respuestas auditivas de estado-estable (ASSR) en el contexto clínico-audiológico pediátrico. Se desarrolló un protocolo para la estimación de umbrales de conducción ósea por medio de ASSR. Se utilizó ruido de banda estrecha por vía ósea para enmascarar las ASSR para un tono modulado de 1.0 kHz. La cantidad de ruido por conducción ósea requerido para enmascarar las ASSR puede ayudar a distinguir entre infantes y niños con hipoacusias conductivas de aquellos con pérdidas sensoriales. La cantidad de ruido por conducción ósea puede ser también utilizado para estimar los umbrales por vía ósea aunque, sin embargo, la exactitud de esta técnica necesita verificación con umbrales conductuales, para determinar dichos umbrales tonales por vía ósea en infantes. Cuando las ASSR obtenidas se utilizan como parte de la evaluación diagnóstica para infantes y niños en riesgo de pérdida auditiva, los resultados rinden información sobre el perfil audiométrico y la audición residual, lo que ayuda en la toma de decisiones de tratamiento y de habilitación.
Auditory steady-state responses (ASSRs) were initially viewed as a method for estimating residual hearing in infants and children who were being evaluated as candidates for cochlear implantation (Rickards and Clark, 1984; Rance et al., 1998). ASSRs are an effective method for estimating residual hearing, even in infants and children with moderate hearing loss who can benefit from conventional amplification (Rance et al., 1998). Picton and colleagues (1998) have extended the use of ASSRs to the estimation of hearing aid gain. Rance and colleagues (1995), Lins and colleagues (1996), Aoyagi and colleagues (1999), and Perez-Abalo and colleagues (2001) have demonstrated that ASSRs may be used in much the same way as a toneburst-evoked auditory brainstem response (tb-ABR), that is, to estimate the audiogram in children with hearing loss, ranging from mild-to-profound levels.

This report is of two studies in which ASSRs were used in much the same way as audiologists currently use click-evoked ABR (c-ABR) and tb-ABR, that is, as diagnostic measures for infants and children at risk for hearing loss. The first study concerns the estimation of the bone-conduction (BC) thresholds so that sensory hearing losses can be distinguished from conductive losses. The second study reports the results from a pediatric audiology clinic when ASSRs were used routinely as a method of estimating threshold in infants followed in a universal hearing screening program.

**STUDY 1: AN ASSR BONE-CONDUCTION MASKING TEST**

The determination of air-conduction (AC) and BC thresholds is a mainstay of clinical audiology. It is useful to have evoked potential methods for estimating the air–bone gap, particularly in infants and young children, who have a high incidence of middle ear disorders causing conductive hearing loss. Because ASSR can be used for pure-tone threshold estimation, it follows that a protocol for using a BC transducer would permit estimation of BC pure-tone threshold and thus the air–bone gap.

Both c-ABR and tb-ABR protocols have been developed for estimating the air–bone gap (for a review, see Cone-Wesson, 1995). One problem with c-ABRs is that a low-frequency air–bone gap could be underestimated, particularly when there is no hearing loss in the high-frequency range. Because the vast majority of conductive losses in infants and young children are in the low-frequency range, owing to otitis media, the c-ABR may not be the most effective method for estimating low-frequency air–bone gaps. Stapells and Ruben (1989) and Foxe and Stapells (1993) have shown that the 500-Hz tb-ABR is an effective means for detecting and estimating the extent of an air–bone gap in the low frequencies. Furthermore, Yang and colleagues (1987), Stuart and colleagues (1990), Stuart and Yang (1994), and Cone-Wesson and Ramirez (1997) have shown that there are important developmental considerations in applying the BC technique to young infants. Specifically, ABR thresholds for BC stimuli are significantly different in young infants compared with adults with normal hearing (e.g., Gorga et al., 1993). In fact, the BC ABR thresholds for clicks, 500-Hz tone bursts, and 4000-Hz tone bursts in infants appears to be 10 to 15 dB better than for an adult (Cone-Wesson and Ramirez, 1997). These differences are attributed to the immature transmission properties of the infant skull and the smaller dimension of the temporal and mastoid bones relative to the BC oscillator (Stuart and Yang, 1994), as well as greater amounts of acoustic energy transmitted from the BC oscillator to the infant ear canal (Cone-Wesson and Ramirez, 1997).
There are technical challenges when electrophysiologic techniques are used for BC threshold estimation, and the first is the problem of stimulus artifacts. The electrical and mechanical artifact of the BC transducer are substantial. Artifact can obscure the response when using stimuli of several milliseconds in duration, such as low-frequency tone bursts, or for the continuous modulated tones used for ASSR. Stimulus calibration needs careful attention as for any audiometric application. Reference equivalent force threshold levels (REFTLs) for BC clicks and tone bursts have not been established, and there is some variation found in the literature (see Cone-Wesson and Ramirez, 1997, Table 1). REFTLs for infants have not been established using behavioral test methods for clicks, tone bursts, or pure tones.

Lins and colleagues (1996) used amplitude-modulated (AM) tones presented through a BC oscillator to estimate threshold from ASSR in eight normal-hearing adults. They demonstrated that ASSR behavioral threshold differences for BC stimuli were about the same as those for AC stimuli. They did not, however, obtain both AC and BC threshold estimates in the same ears to establish an air-bone gap.

One method for testing BC thresholds is based on Rainville’s “sensorineural acuity level” (SAL) test (Jerger and Tillman, 1960; Dirks, 1973). With the SAL technique, the amount of effective masking (EM) delivered through a BC oscillator is used to estimate BC threshold. First, the amount of BC noise needed to mask an AC tone near threshold is determined for a panel of normal-hearing listeners. For patients with conductive hearing loss, the AC threshold for the test tone will be elevated, but the amount of BC masking noise will be the same as for normals (e.g., 0–15 dB EM). For those with sensorineural hearing losses, the amount of BC noise to achieve EM will be elevated with the pure-tone threshold. For mixed losses, the level of BC masking estimates the amount of sensory hearing loss, whereas the difference between the AC threshold and the masking level indicates the amount of conductive loss.

The technique was first adapted to BC ABR tests by Hicks (1980), who demonstrated its use in infants and in adults with simulated conductive losses. Later, Ysunza and Cone-Wesson (1987) demonstrated the sensitivity and specificity of the technique in a group of infants and children with congenital ear anomalies. Webb and Greenberg (1983) used AC tone bursts masked by white noise to estimate BC thresholds, whereas Janssen and colleagues (1993) developed correction factors for estimating the size of the air–bone gap.

The purpose of this study was to apply the SAL technique with ASSR for estimating BC thresholds in infants at risk for hearing loss.

**Participants**

The 39 infant participants, including 24 females, were recruited and tested at ages 3 to 13 weeks (mean = 8 weeks) corrected age. All infants had risk factors for hearing loss: a family history of hearing loss for 21 participants, pinna or other ear anomalies for 5 participants, birthweight < 1500 g for 4 participants, and hyperbilirubinemia with exchange transfusion for 3 infants. There were 2 infants with syndromes (Down and Aicardi’s), and parental concern and birth trauma were also considered risk indicators. In addition, 2 children with sensorineural hearing losses documented by pure-tone audiometry were tested.

**Procedures**

All infants had a c-ABR threshold test, a distortion-product otoacoustic emission (DPOAE) test, and a tympanogram. ABRs were obtained using a Sapphire 2ME Medelec evoked potential test system. Clicks of alternating polarity were presented at a rate of 30/sec through TDH-49P circumaural phones. Clicks at 0 dB nHL had a peak equivalent sound pressure level of 33 dB. ABRs were recorded from a high forehead (Fz)-ipsilateral mastoid (Mi) electrode montage, with the electroencephalogram (EEG) filtered at 100 to 2000 Hz. ABR tests were initiated at 50 dB nHL with two trials of 1024 sweeps each collected at each test level. When the ABR waveforms obtained in the two trials were judged by the examiner to be replicable, the stimulus level was decreased in 20- or 10-dB steps until no replicable response was obtained. Two additional trials were conducted at 10 dB above the level at which no ABR was present to confirm threshold.

DPOAEs were obtained using the Otodynamics ILO92 system. The level of the primary tones was 65 and 50 dB SPL for F1 and F2, respectively, and a frequency ratio of F2/F1 = 1.22. DPOAEs were recorded for the frequency range of 1.5 to 6 kHz in 1/8-octave steps.

A GSI 33 Middle-Ear Analyzer was used to obtain the tympanograms. Probe tones at 678 or 1000 Hz were used, with a pressure sweep from +200 to −400 daPa.
ASSR thresholds were determined for a 100 percent AM + 15 percent frequency-modulated 1.0-kHz tone, presented at a modulation frequency (MF) of 81 Hz through insert earphones and calibrated in dB HL (as for a pure tone at the same frequency). Stimulus presentation and ASSR data acquisition were controlled by the ERA System (Appendix). The electrode montage was the same as for the ABR test. Stimulus trials were initiated at 50 dB HL, and the stimulus level was increased or decreased based on the results of the phase coherence (PC) analysis of the sampled trials (Cone-Wesson et al., 2002a). The lowest level at which a statistically significant (p < .01) phase-locked response was obtained was deemed to be threshold. Once threshold had been determined, the tone was presented at 10 dB re ASSR threshold. One-third octave narrow-band noise, generated by a Madsen OB-22 clinical audiometer, centered at 1.0 kHz, was introduced via a RadioEar B70 BC oscillator, which was placed superior and posterior to the mastoid bone in the position recommended by Stuart and colleagues (1990), using a custom-made elastic and Velcro headband. The elastic band was adjusted to maintain a vibrator-to-head coupling force of 325 ± 25 g, which was measured with a spring scale (Ohaus model 5413). The level of the masking noise was increased from 0 dB nHL in 10-dB steps until the PC' ASSR detection algorithm returned a nonsignificant (p > .01) “random” result (Cone-Wesson et al., 2002a). The level of BC noise needed to obtain a random result for a 10 dB (re ASSR threshold) was recorded.

The narrow-band noise (NBN) levels were calibrated using psychophysical and electroacoustic methods. First, a panel of 10 female adults with normal hearing was used to determine psychophysical threshold for the BC NBN at 1.0 kHz. The levels of masking noise were calibrated re 1 μV using the formula 20 log Vm/1V, where m is the masker level, in volts, measured from an oscilloscope when the BC oscillator was coupled to an artificial mastoid (Bruel and Kjaer Type 4930) connected to a Brue and Kjaer Sound Level Meter (Type 2235) and octave filter set (Type 1625). The 0 dB nHL level for the BC NBN at 1000 Hz was 26 dB re 1 V.

**Results**

For each of the 39 infants, the c-ABR threshold, tympanogram type, presence or absence of DPOAEs, 1.0-kHz ASSR threshold, and amount of BC noise needed to mask the AC ASSR + 10-dB threshold were determined. The same procedure was followed for the two older participants, but instead of obtaining an ABR threshold, pure-tone audiometry was performed.

**ASSR and ABR Thresholds**

ASSR threshold increased with c-ABR thresholds, and this is described by the regression equation (ASSR threshold) = 1.023 (ABR threshold) + 8.091, with an r² of 0.62. The data were then segregated into two groups, one consisting of ASSR thresholds from infants with ABR thresholds > 20 dB nHL (n = 10) and those with ABR thresholds at ≤ 20 dB nHL (n = 29). The mean 1.0-kHz ASSR threshold for the normal ABR group was 26 dB HL, and for the abnormal ABR group it was 61 dB HL, a difference that was statistically significant (t_{df=37} = 8.354, p < .01).

**Tympanometry and DPOAE Tests**

Tympanograms were typed using three classifications: normal, flat, or negative peak. A normal tympanogram had a peaked appearance, with the maximum admittance value occurring within ±50 daPa of 0 daPa pressure. Flat tympanograms had no admittance peak within the range of +200 to -200 daPa of applied pressure. Negative peak tympanograms had an admittance peak that occurred at ~100 daPa or greater. There were 24 ears with normal tympanograms, 12 with flat tympanograms, and 5 with negative peaks.

DPOAEs were classified as present when a signal-to-noise ratio of 3 dB was achieved for the frequency range 1.5 to 6 kHz (3 points/octave) and absent when the signal-to-noise ratio was less than 3 dB. DPOAEs were present for all infants with a normal tympanogram and ABR thresholds at ≤ 20 dB nHL. DPOAEs were absent for four infants who had normal tympanograms but ABR thresholds in the 40 to 100 dB nHL range. DPOAEs were absent for all infants with

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1 Rather than attach a loop of nylon thread to the BC oscillator (Stuart et al., 1990), we used a piece of 2-cm-wide ribbon. This could be placed perpendicularly underneath the BC oscillator, a loop tied at the top for coupling to the spring scale, and thus the oscillator could be lifted from the skull and the coupling force measured. The placement of the oscillator may wake the baby, however, he/she can be lulled back to sleep. The coupling force used in this study was 100 g less than that used by Stuart et al (1990) and was well tolerated by most infants.
Figure 1  ASSR thresholds for an AC 1.0-kHz AM + FM tone are shown with the BC NBN masker levels needed at ASSR + 10 dB. Control group had normal DPOAE, ABR, and tympanogram tests. Indeterminate group had absent DPOAEs, normal ABRs, and abnormal tympanograms. The presumed conductive group had absent DPOAEs, elevated ABR thresholds, and an abnormal tympanogram. The clinical history also suggested middle ear disorder. The presumed sensorineural group had absent DPOAEs, elevated ABR thresholds, and normal tympanograms. A flat tympanogram, even in infants who had ABR thresholds ≤ 20 dB nHL. Four infants with a negative peak tympanogram and ABRs present at ≤ 20 dB nHL had DPOAEs present.

BC Masking for Infants with Normal ABR, DPOAE, and Tympanograms

The amount of BC masking used to mask the response to an AC stimulus, for infants grouped on the basis of ABR, tympanogram, and DPOAE results, is illustrated in Figure 1. Nineteen infants with an ABR threshold ≤ 20 dB nHL, a normal tympanogram, and DPOAEs present were selected as the group of normal controls. The mean AC 1.0-kHz ASSR threshold in this group was 23 dB HL, and the mean amount of BC NBN needed to mask the ASSR + 10-dB response was 13 dB nHL (range 10–20 dB nHL).

BC Masking in Infants with Normal ABR Thresholds

There were nine infants who had elevated ABR thresholds, ranging from 40 to 60 dB nHL. Their 1.0-kHz ASSR thresholds ranged from 40 to 80 dB HL, with a mean of 60 dB HL. There were three infants with normal tympanograms and six with flat tympanograms; DPOAEs were absent for all of these infants. The amount of BC NBN needed for the infants with normal tympanograms was 53 dB nHL, an estimated air–bone gap of only 7 dB. In contrast, for the infants with flat tympanograms, masking was achieved with only 18 dB nHL of BC NBN, an estimated air–bone gap of 40 dB. Two children with sensorineural hearing losses were also tested. Pure-tone thresholds for one child were 35, 45, 65, and 85 dB HL in the range of 500 to 4000 Hz, tested in octave steps. The pure-tone thresholds for the second child were 20, 40, 55, and 60 dB HL in the same frequency range. Their ASSR thresholds and BC masking levels were elevated commensurate with their pure-tone audiograms, that is, NBN levels of > 50 dB nHL were needed.

Discussion

The main application of threshold estimation by AC and BC evoked potentials is for young infants or developmentally disabled children for whom behavioral tests are not possible. Differential diagnosis of conductive versus sensorineural hearing loss is needed for audiolologic and medical management, so an estimation of AC and BC thresholds will help to determine appropriate intervention. The present study demonstrated that it was possible to estimate AC and BC masking thresholds in infants at risk for hearing loss, and this was particularly useful for those who failed standard screening tests (c-ABR and DPOAE).

The SAL method adapted for ASSR was able to separate infants with hearing loss into infants with negative-peak tympanograms with normal ABR thresholds. Their mean ASSR threshold was 35 dB HL, and the amount of noise for masking was 17 dB HL. The differences in AC ASSR threshold and BC NBN levels for the 10 infants who had normal ABRs and nonnormal tympanograms were not significantly different from the 19 control infants with normal ABRs and tympanograms (F = 0.02, df = 1, p > .05).
conductive and sensorineural hearing loss groups. There were nine infants with elevated ABR (and ASSR thresholds) and absent DPOAEs. For three infants with ABR (and ASSR) thresholds > 40 dB HL and normal tympanograms, the amount of BC NBN needed for effective masking was close to the AC ASSR threshold, suggesting a sensorineural loss. For 6 infants with similarly elevated ABR and ASSR thresholds and flat tympanograms, only 18 dB nHL of BC masking was needed, just 6 dB more than for infants with normal thresholds, tympanograms, and DPOAEs. These findings suggest a conductive-type impairment. This pattern of findings for ASSR is similar to studies in which SAL techniques were used with ABR, that is, BC masking levels were elevated in those with a sensorineural loss compared with those with normal hearing or conductive losses (Webb and Greenberg, 1983; Ysunza and Cone-Wesson, 1987).

The most obvious limitation to this study is a lack of behavioral confirmation of the threshold estimates obtained by ASSR. It is the case, however, that there are no BC pure-tone threshold norms for infants and toddlers. That their BC thresholds might be vastly different from older children and adults is certainly indicated by every evoked potential measure that employed BC signals (Yang et al, 1987; Stapells and Ruben, 1989; Cone-Wesson and Ramirez, 1997). In each of these studies, BC thresholds in infants were estimated to be well below those for older children and adults. The characteristics of a transient stimulus reaching the cochlea will be altered by the transmission properties of the skull (Arlinger et al, 1978; Harder et al, 1983), and the infant skull differs markedly from the adult skull. The use of reference threshold levels based on adult thresholds will be inappropriate for application to infants. For infants under the age of 6 months, it is unlikely that AC and BC thresholds can be established behaviorally using standard clinical techniques. Additional verification of the method proposed here may be accomplished by determining AC and BC ABR thresholds for toneburst stimuli and then using those as a “gold standard” against which the SAL ASSR method can be compared.

Should a correction factor be used to estimate BC thresholds in infants? That is, should the 13 dB nHL masking levels obtained in 19 infants with otherwise normal test results be considered the “normal” BC threshold, assuming no air-bone gap, or should we assume that if 13 dB nHL BC NBN masks the ASSR threshold (23 dB HL), there is a 10-dB air–bone gap? Preliminary data obtained from older children are inconclusive. Until such time as we can obtain behavioral measures of threshold for BC tones, we will presume that the BC NBN level estimates the BC threshold. For the control group of infants with normal AC ABR and ASSR thresholds, DPOAEs, and tympanograms (N = 19), the BC NBN level was 13 dB nHL. We propose that any BC NBN masking levels above 22 dB nHL (mean + 2 SD) should be considered suggestive of a sensory component to the hearing loss.

There are several advantages to the SAL technique for evoked potential tests. First, the stimulus used to evoke the response is an AC signal delivered through insert phones. As such, the interaural attenuation for these signals is at least 50 dB SPL for low- and mid-frequency tones. This allows for ear-specific testing and avoids the masking dilemmas inherent when using BC stimuli. Although Yang and colleagues (1987) showed that interaural attenuation for BC may be as great as 35 dB for infants < 6 months, if there is any crossover of the BC noise, it will only serve to mask a contribution of the nonetest ear. The presentation of masking by BC and stimulus by AC also lessens the probability that stimulus artifact will taint the recording. Although the BC oscillator will create both electrical and mechanical artifact, the nature of the artifact (i.e., noise) is more amenable to signal processing solutions than is an artifact that mimics the response (such as the “ringing” of the BC oscillator with a click stimulus or a modulated tone for ASSR). There are output limitations of the BC oscillator that prevent the determination of thresholds poorer than about 50 dB HL. This is the same limitation that exists for conventional pure-tone BC threshold tests.

Why not use BC presentation of AM + FM tones to estimate ASSR thresholds? This is another possibility, but until the technical issues regarding artifact have been addressed, it is not recommended. Normal BC ASSR thresholds for young infants have not yet been published, and the lack of age-specific norms limits clinical interpretation.

Audiogram estimation for both AC and BC stimuli is a time-intensive procedure. With the ASSR acquisition software used in this study (ERA System), it generally takes 4 to 5 minutes to estimate a threshold at a given frequency. The ERA system analyzes 20 to 64 EEG samples (each sample duration is 1.5 sec) for each trial at a specified stimulus level. Responses obtained...
at suprathreshold levels are robust and meet the statistical criterion in under 1 minute (Cone-Wesson et al., 2002b); however, longer sampling times (up to 64 samples, or 96 sec) are needed at lower stimulus levels. A four-frequency audiogram can be estimated in about 20 minutes from a quietly sleeping infant—double that time if BC thresholds are sought at each frequency. We believe that a BC test at 1.0 kHz is a good choice for an initial test and may be sufficient for most clinical situations. We reasoned that a test for a conductive loss at 1.0 kHz would likely yield information important for audiologic management and would supplement information obtained from AC tests and tympanometry. ASSRs are more robust at 1.0 kHz than at lower frequencies, and this is an advantage too. If AC thresholds are elevated at 1 kHz, a test for conductive hearing loss could be completed very quickly by presenting BC NBN at 20 dB nHL. If the ASSR + 10 is masked by this noise, then a conductive loss is present. If more than 20 dB nHL is needed to mask the ASSR + 10, then a sensory component to the loss is suspected. The threshold for BC can be estimated by tb-ABR methods or by finding the effective (BC) masking level.

ABR tests employing BC stimuli or masking methods have proven beneficial for pediatric diagnostic audiology. The results of this study provide a rationale and methodology for BC ASSR tests that extend the diagnostic efficacy of evoked potential procedures by using frequency-specific stimuli.

STUDY 2: CLINICAL TRIAL OF AN ASSR SYSTEM IN A UNIVERSAL HEARING SCREENING PROGRAM

In 1998, the ERA System for recording ASSRs was commercially released in the Asia-Pacific region. The Royal Children’s Hospital (RCH) of Melbourne, Australia, was the first site in Australia to use the ERA System on a routine basis for testing infants and young children at risk for hearing loss. This is a report of the RCH clinical experience with the ERA System. The RCH site was ideal for this clinical trial because the site at which study 1 was conducted; one of the audiologists at the RCH had used prototype ASSR technologies for over 10 years and had completed a pilot study establishing a ASSR test protocol (Tan, 1998). In addition, the RCH is a major audiology center for the Victorian Infant Hearing Screening Program (VIHSP). Infants with risk factors for hearing loss receive an ABR test before 3 months of age as part of the VIHSP. As well, infants who fail behavioral hearing screening tests (provided at community health centers) at 7 to 9 months are referred for diagnostic testing and follow-up as part of the VIHSP. The RCH is one of the major pediatric audiology centers for the state of Victoria.

For infants under the age of 6 months and for older infants who were developmentally disabled, c-ABR, otoacoustic emissions, and tympanometry were all used routinely for diagnostic evaluations at the RCH. When the ERA System became available, ASSRs were incorporated into the diagnostic protocol. This study reports the use of ASSRs in a hospital-based pediatric audiology program.

Method

The sample consisted of 85 infants and children (41 females) who received ASSR tests during an 18-month clinical trial of the ERA System. There was no preselection for inclusion in the data set. The data were collated from post hoc chart review. The data extracted from the medical records were medical history, ABR test results (from waveforms and summary report), ASSR test results (thresholds and summary report), tympanometry results (summary report), behavioral test results (audiogram and summary report), and otoacoustic emissions (summary report). Only those infants who had both ABR and ASSR results were included in the current data analyses. From a pool of 137 infants and children referred for diagnostic evaluation during the review period, 85 had both ABR and ASSR results; as well, tympanometry results were available for the majority but behaviorally determined minimum response levels and evoked otoacoustic emissions (EOAEs) for less than 25 percent of the group. The behavioral data were usually obtained months after the ABR and ASSR tests, and in some cases, treatment for otitis media had taken place in the interval between evoked potential and behavioral threshold estimates. This being the case, and because there was such a limited amount of behavioral data, a comparison between behavioral and electrophysiological threshold estimates was not completed.

The standard clinical protocol was followed for ABR and ASSR tests. Eighty percent of the tests were conducted during natural sleep, oral sedation (chloral hydrate) was used in 15 percent of the trials, and approximately 5 percent of the tests were conducted in the operating theater under general anesthesia. Except for
those studies done in the operating theater, the tests took place in a sound-treated room in the Audiology Department of the RCH. The protocol consisted of first obtaining a c-ABR for each ear: tests commenced at 40 dB nHL, and the level decreased in 10-dB steps to 20 dB nHL if responses were present or increased to 60 dB nHL if responses were absent. If absent at 60 dB nHL, the level was increased by 10 dB nHL until a response occurred, up to a level of 100 dB nHL. Threshold was reported as the lowest level at which an ABR was detected. ASSR threshold tests were then completed. The order of ears tested was determined by the audiologist, and if one ear had abnormal ABR results, then that was the ear tested first for ASSR. The order of test (carrier) frequency was usually 1000, 500, 4000, and 2000 Hz, although this was left to the discretion of the audiologist, based on her prior knowledge of the infant's risk factors and medical and audiologic history. ASSR threshold tests commenced at a level of 40 to 60 dB HL, and 10-dB steps were used to bracket threshold. Threshold was taken as the lowest level at which a statistically significant “phase-locked” response was returned by the PC$^2$ algorithm. Following ABR and ASSR tests, tympanometry was conducted, and measurement of EOAEs was included if the child was still in a cooperative state.

For some infants, there were multiple test sessions (up to four) to obtain data for both ears at several frequencies; the duration of natural sleep was very brief for some infants, necessitating multiple visits. Also, it was not possible to obtain thresholds for all four test frequencies for all ears; this was often the case for those infants with normal ABR results: when there was less concern that significant hearing loss was present, there was less motivation for the infant to be brought back for repeated tests. Some infants underwent testing of the same ear on more than one occasion: this was more common among those with significant hearing losses indicated by both ABR and ASSR tests, whereas those with normal ABR results were rarely tested more than once. The data in this analysis will be reported for “ears” and tests rather than for individual children.

The mean chronologic age of the patients at the time of the ASSR test was 11.5 months, although the median age was 4 months and the mode 1.5 months. The range of ages in the sample was from the newborn period up to 79 months. The median and modal age reflect the fact that most infants were tested as part of the VIHSP and had neonatal risk factors for hearing loss, such as premature birth, hyperbilirubinemia, or a history of deafness in the family. Infants with risk factors for hearing loss had ABR and ASSR tests before 3 months of age.

### Results

#### ASSR Threshold

The ASSR data were sorted according to the c-ABR result. Ninety-one ears had an ABR threshold of 20 or 30 dB nHL. ASSR thresholds as a function of carrier frequency are shown in Table 1. ASSR thresholds were 60 dB or lower for this group. The mean threshold was lowest at 2 kHz (26 dB HL) and highest at 500 Hz (39 dB HL). The difference in ASSR threshold as a function of frequency is significant ($F = 10.786$, $df = 3, 189$, $p < .01$), with post hoc analyses revealing that the differences between 500 and 2000 Hz, 1000 and 2000 Hz, and 2000 and 4000 Hz were significant at the $p < .05$ level.

The ASSR thresholds in this subgroup were then examined with respect to tympanometry result. There were 67 ears for which both ASSR threshold and tympanometry results were available. Thresholds were sorted into normal versus abnormal groups, with thresholds obtained from those who had peak compensated normal admittance at 0 dB daPa considered normal and thresholds associated with a flat (no peak), low-admittance tympanogram placed in the abnormal group. There were 44 normal tympanograms and 23 abnormal tympanograms. The trend was for those who had normal tympanograms to have slightly better thresholds (mean difference of 4.5 dB) than those with flat tympanograms ($t_{1-tailed} = 1.64$, $p = .052$). ASSR thresholds were also evaluated with respect to c-ABR threshold, 20 dB nHL versus 30 dB nHL, regardless of tympanometric status. There were no significant differences in ASSR threshold

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</table>
that were related to these small c-ABR threshold differences.

There were 68 infants who had at least one ear with an ABR threshold exceeding 30 dB nHL, including 34 ears in which ABRs were absent at the attenuator limits (110 dB nHL). The ASSR data for these infants were also sorted by ABR threshold.

ASSR thresholds for 15 ears with ABR thresholds at 40 or 50 dB nHL are graphed in Figure 2A using an audiogram format. It was not always possible to obtain threshold estimates for all four frequencies on each ear. The figure shows that most of the ASSR thresholds are in the range of 40 to 70 dB HL. There are upward-sloping, flat, and downward-sloping configurations evident. Abnormal tympanograms were typically found for those with thresholds poorer than 60 dB HL at 500 Hz.

Figure 2B shows the ASSR results for five ears that had ABR thresholds at 60 or 70 dB nHL. All of the ASSR thresholds were between 60 and 100 dB HL, with the majority of thresholds falling at 60 to 80 dB HL, very close to the ABR threshold. The results for ears (n = 7) that had ABR thresholds at 80, 90, or 100 dB nHL are similar to those from the previous group in that most of the ASSR thresholds were found in the same range, 70 to 100 dB nHL, as the c-ABR (Fig. 2C). The symbols plotted at 110 dB HL indicate a response at that level; higher levels were not tested at other frequencies for these ears.

Finally, Figure 2D illustrates the ASSR thresholds obtained when there was no response at 100 dB nHL for c-ABR. In these cases, higher stimulus levels were used for ASSR tests, so residual hearing is indicated at 110 to 120 dB nHL for some cases. For the majority of ears in which ABRs were absent at attenuator limits, so, too, were the ASSRs at two or more frequencies tested. There were 34 ears for which ABR showed no response, and of those, 21 also had no ASSR for modulated tones presented at 110 dB HL.

Figure 3 is a scatter plot of ASSR thresholds as a function of ABR threshold, with carrier frequency as the parameter. The scatter plot includes only those data for which a response was recorded and excludes those with absent ABR or ASSR responses. The regression formulae are shown in the figure legend. The regression of ASSR with ABR thresholds was highest for 4 kHz, with \( r^2 = .62 \). The regressions were statistically significant (p < .05) for ASSR test frequencies of 1, 2, and 4 kHz.

Discussion

The ASSR threshold data from infants and children with normal c-ABR thresholds replicate and extend the reports of Lins and colleagues (1996) and Rickards and colleagues (1994) concerning normative data in young infants. For comparison, mean thresholds obtained in each study are provided in Table 2. The largest discrepancy between Ottawa (Lins et al., 1996) and Melbourne I (Rickards et al., 1994) and II (present study) is at 4 kHz. There were considerable differences in procedure as Lins and colleagues (1996) used simultaneous presentation of 4 AM tones, whereas at the RCH, tests were conducted with AM + FM tones presented individually. It is difficult to know whether and how the differing techniques led to a threshold discrepancy at only one frequency. One possibility is that the use of combined AM + FM tones requires careful consideration of the phase of each type of modulation. It may be that at 4 kHz, AM alone is a better stimulus than combined AM + FM unless the phase of FM relative to AM is optimized.

The RCH-Melbourne and Ottawa data suggest some improvement in threshold with maturation, particularly at 500 Hz and 4 kHz, in comparison with the Rickards and colleagues (1994) threshold data from newborns. For clinical determinations, a summary of these three studies indicates that ASSR thresholds at or above 60, 50, 45, and 55 dB SPL at 0.5, 1, 2, and 4 kHz, respectively, should be considered abnormal.

Middle ear status, as defined by tympanometry, had a small (4 dB) effect on ASSR threshold for infants with c-ABR at 30 dB nHL or better. There were children with low-admittance, flat tympanograms who had ABR thresholds at 20 dB nHL and those with normal tympanograms who had thresholds at 30 dB nHL. This is not surprising because normal pure-tone thresholds are sometimes found in older children who have middle ear effusion. Furthermore, the c-ABR at 30 dB nHL may not be sensitive to hearing loss caused by effusion in early infancy (Cone-Wesson et al., 2000). Post hoc analyses of the ASSR thresholds showed that the effect of middle ear status was largest at 1.0 kHz (6-dB difference), but that at 500 Hz, the mean threshold for infants with flat-type tympanograms was 2 dB better than for those with normal tympanograms. This was a sampling error in that there were only nine thresholds obtained at 500 Hz associated with an abnormal tympanogram (compared with 14 with normal tympanograms), but for the ears tested.
Figure 2 A, ASSR thresholds as a function of frequency for infants and children who had c-ABR thresholds at 40 or 50 dB nHL. B, ASSR thresholds as a function of frequency for infants and children who had c-ABR thresholds at 60 or 70 dB nHL. C, ASSR thresholds as a function of frequency for infants and children with c-ABR thresholds at 80, 90, or 100 dB nHL. D, ASSR thresholds as a function of frequency for infants and children with absent c-ABR at 100 dB nHL. (Each symbol represents one subject; symbols connected with lines represent that more than one ASSR threshold was determined for that individual.)
those of Rance and colleagues (1998), who showed that ASSRs could be present for many children with moderate-to-profound degrees of hearing loss for whom c-ABRs were absent. In this study, however, it was more often the case that when ABRs were absent, so too were ASSRs. One reason for this may be that the RICH test protocol did not generally allow presentation of stimuli above 110 dB HL, although the output limits are 10 dB above that at some frequencies. There has been some criticism of using prolonged, high-intensity tones (Stapells, 2000), as are needed for ASSR threshold estimates for those who have severe-to-profound hearing loss. With the ERA System, the exposures are limited to durations of 104 sec or less for each frequency-level combination. This is not the case with some other systems for which up to 10 minutes of stimulation are needed to define threshold (Herdman and Stapells, 2001). When testing infants who have no response for c-ABRs, the risk of damage owing to noise exposure must be weighed against the benefit of determining residual hearing for decisions about amplification, cochlear implantation, or other habilitation (Stapells, 2000).

Analysis of ASSR thresholds with respect to ABR thresholds showed that there was excellent correspondence between ASSR thresholds at 1, 2, and 4 kHz and the c-ABR threshold. Overall, both ASSR and ABR can be used to estimate the degree of hearing loss; however, the ASSR can contribute additional knowledge regarding audiometric contour.

**Table 2  ASSR Thresholds in dB SPL, Summarized from 3 Studies of ASSR Threshold in Infants**

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Rickards and Colleagues (1994) Melbourne 1</th>
<th>Royal Children's Hospital, 2001 Melbourne II</th>
<th>Lins and Colleagues (1996) Ottawa</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>53 (SD = 10)</td>
<td>45 (SD = 8)</td>
<td>45 (SD = 13)</td>
</tr>
<tr>
<td>1000</td>
<td>31 (SD = 8.5) (1500 Hz)</td>
<td>34 (SD = 10)</td>
<td>29 (SD = 10)</td>
</tr>
<tr>
<td>2000</td>
<td>31 (SD = 8.5) (1500 Hz)</td>
<td>29 (SD = 9.5)</td>
<td>26 (SD = 8)</td>
</tr>
<tr>
<td>4000</td>
<td>45 (SD = 11)</td>
<td>38 (SD = 12)</td>
<td>29 (SD = 10)</td>
</tr>
</tbody>
</table>

**FINAL THOUGHTS**

ASSRs have been used in audiology research centers around the world for the past decade. The results from clinical studies have shown that ASSR thresholds can be used to predict pure-tone threshold in sleeping infants and young children (Rance et al, 1995, 1998, 2002; Perez-Abalo et al, 2001). ASSR, therefore, should have an increasing role in the follow-up and
diagnostic evaluation of infants who have failed newborn hearing screening. The research studies reported here show how ASSRs perform in a clinical pediatric audiology setting. Used in conjunction with ABR, ASSRs provide additional information about the contour and degree of any existing hearing loss.

There are questions that remain. First, the neural generators of the response are still in dispute, particularly as a function of MF. This should not limit adoption of ASSRs in the clinic; the precise sites and structures involved in the ABR have not been fully defined either. Second, the effect of neuromaturation and neurodevelopmental insult on the ASSR is a critical issue for investigation. A related issue is the definition of normal “threshold” for the ASSR as a function of age; this would be expected to vary with both maturation of the auditory system periphery and the central auditory nervous system. Third, the use of multiple simultaneous carrier frequencies for ASSR evaluations could prove useful for evaluating the kind of processing that underlies speech perception (Dimitrijevic et al., 2001). Tests for speech discrimination and perception have relied on cognitive event-related potentials for complex sounds and synthesized speech but have not had overwhelming success for clinical applications (Dalebout and Stack, 1999; Dalebout and Fox, 2000). With the current development of early identification and intervention for hearing loss programs, there is a pressing need to evaluate speech perception and make decisions regarding aural habilitation in infants and young children. Evoked potentials for AM and FM tones, presented alone or in combination, may prove to be beneficial in this regard.

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REFERENCES


**APPENDIX**

**ERA System Specifications**

Stimulus generation and data acquisition are programmed on a Motorola DSP56002FC66 processor and interfaced with a personal computer running a Windows operating system at 66 MHz or higher. The EEG is recorded using scalp electrodes placed at the vertex and ipsilateral earlobe or mastoid and led to an Intelligent Hearing Systems Opti-Amp 3000D preamplifier. EEG samples of 1486 msec in length, sampled at 44.1 kHz, are filtered at 3.0 to 5000 Hz and amplified with a gain of 70 dB. Up to 64 samples of 1486 msec each are subjected to a fast Fourier analysis, and the coherence is evaluated using the PC³ algorithm (Dobie and Wilson, 1993).