Hearing Threshold Estimation in Infants Using Auditory Steady-State Responses

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Abstract

Successful early intervention in children with permanent hearing loss requires assessment techniques that can accurately reflect the behavioral audiogram in infancy. This retrospective study compared auditory steady-state response (ASSR) findings from subjects tested in the first three months of life with subsequently obtained behavioral hearing levels. ASSR audiograms were established using amplitude and frequency modulated tones at octave frequencies (500 Hz to 4 kHz). Results obtained from 575 subjects including 285 with normal hearing, 271 with sensorineural hearing loss, and 19 with auditory neuropathy-type hearing loss are presented. ASSR and behavioral hearing thresholds for subjects in the normal and sensorineural groups were highly correlated, with Pearson $r$ values exceeding 0.95 at each of the test frequencies. In contrast, ASSR thresholds in children with AN-type hearing loss did not accurately reflect the behavioral audiogram. Overall, the findings indicate that ASSR testing can offer useful insights into the hearing acuity of children tested in infancy.

Key Words: Auditory steady-state response, hearing, infants

Abbreviations: ABR = auditory brainstem response; AN = auditory neuropathy; ASSR = auditory steady-state response; NICU = neonatal intensive care unit

Sumario

Una intervención temprana exitosa en niños con trastornos auditivos exige técnicas que puedan reflejar con exactitud un audiograma conductual en la infancia. Este estudio retrospectivo compara los hallazgos con respuestas auditivas de estado estable (ASSR) de sujetos evaluados en los primeros tres meses de vida, con los niveles auditivos conductuales obtenidos subsecuentemente. Se establecieron audiogramas por ASSR utilizando tonos modulados en frecuencia y amplitud por octava (500 Hz a 4 kHz). Se presentan los resultados obtenidos de 575 sujetos, incluyendo 285 con audición normal, 271 con hipoacusia sensorineural y 19 con pérdidas auditivas tipo neuropatía auditiva. Los umbrales de ASSR y los umbrales auditivos conductuales en los grupos de sujetos con audición normal y con hipoacusia sensorineural tuvieron una alta correlación, con valores Pearson por encima de 0.95 en cada una de las frecuencias evaluadas. En contraste, los umbrales ASSR en niños con hipoacusia tipo AN no reflejaron con exactitud el audiograma conductual. Globalmente, los hallazgos indican que la evaluación con ASSR puede ofrecer...
Recent evidence has confirmed the long-held belief that early diagnosis and intervention can ameliorate the damaging effects of congenital hearing loss. Studies by Yoshinaga-Itano et al (1998) and Moeller (2000), for example, have shown that the provision of appropriate amplification and educational support within the first six months of life maximizes the potential for long-term speech and language development in children with all degrees of permanent hearing loss. Determination of this critical intervention period (zero to six months) has provided an impetus for the establishment of universal neonatal and infant hearing screening programs worldwide whose aim is to identify affected youngsters within the first few weeks of life. However, identification is only the first step in the successful management of a hearing-impaired child. Intervention processes, in particular the fitting of appropriate hearing aids, require audiometric profiles that accurately reflect both the degree and configuration of a child’s hearing loss. As behavioral hearing measures in children less than six months of age cannot provide this information (Davis et al, 1991; Ling et al, 1970), nonvolitional assessment procedures such as those based upon auditory evoked potentials have become the tests of choice for this age group.

The auditory steady-state response (ASSR) is one such evoked potential whose applicability for the assessment of hearing in infants and young children has been investigated over the past decade (Rickards et al, 1994; Aoyagi et al, 1999; Cone-Wesson, Parker, et al, 2002; Cone-Wesson, Rickards, et al, 2002; Rance and Briggs, 2002; Rance and Rickards, 2002). Auditory steady-state responses are scalp potentials that can be elicited in response to periodically varying stimuli such as sinusoidal amplitude and/or frequency modulated tones. The resulting response is periodic and is phase locked to the modulation envelope of the stimulus tone. ASSRs can be obtained for a wide range of modulation frequencies (Rickards and Clark, 1984), but rates around 70 to 100 Hz have proven most successful for assessment of sleeping babies (Levi et al, 1993; Rickards et al, 1994).

Auditory steady-state response testing using modulated tones has a number of advantages in estimating the behavioral audiogram over techniques that require short duration stimuli (such as the auditory brainstem response). The continuous nature of the tones means that they do not suffer the spectral distortion problems associated with acoustic clicks or tone bursts. As such, they are reasonably frequency-specific and allow the generation of an “evoked potential audiogram” that can reflect the pattern of a subject’s hearing thresholds (Rance et al, 1995; Lins et al, 1996; Aoyagi et al, 1999). Another particular advantage afforded by the continuous stimulus is that the tone can be presented at high levels (up to 120 dBHL at most test frequencies) enabling assessment of ears with only minimal amounts of residual hearing (Rance et al, 1998; Stueve and O’Rourke, 2003; Swanepoel et al, 2004).

Auditory steady-state responses can be
recorded in sleeping subjects of all ages (Aoyagi et al., 1993; Rickards et al., 1994; Cone-Wesson, Parker, et al., 2002). Stimuli modulated at rates around 70–100 Hz have been shown to elicit potentials (with equivalent latencies of approximately 10 msec) in normally hearing neonates at levels around 25–40 dBHL. Auditory steady-state responses have also been studied in young children with varying degrees of sensorineural hearing loss (Rance et al., 1995, 1998; Lins et al., 1996; Aoyagi et al., 1999; Rance and Briggs, 2002; Rance and Rickards, 2002; Vander Werff et al., 2002; Stueve and O'Rourke, 2003; Swanepoel et al., 2004). ASSR thresholds in these investigations have been highly correlated with behavioral hearing levels and have typically been obtained at low sensation levels (≈5–10 dB).

This retrospective clinical study further investigates the relationship between ASSR and behavioral hearing thresholds in young children. In particular it involves a comparison of ASSR findings obtained in infancy with subsequently established behavioral hearing levels for a group of 575 children with hearing thresholds ranging from normal to profound levels. Results for ears with normal hearing, sensorineural hearing loss, and auditory neuropathy-type hearing loss are presented.

**METHODS**

Clinical findings from the seven metropolitan and regional diagnostic audiology clinics in the state of Victoria (Australia) with ASSR assessment capabilities are presented in this study. Identical test procedures were employed in these centers, and in each case, the auditory steady-state response assessments were undertaken using either the ERA Systems, or GSI AUDERA®, commercial evoked potential devices. The data represents results obtained for every young child who underwent ASSR testing at these centers (and who met the selection criteria) over a five-year period from 1998 to 2003.

Subjects were included in the study if they had undergone the ASSR assessment at an (corrected) age of ≤3 months and if they had subsequently shown reliable hearing thresholds when tested using conditioned audiometric procedures. In order to reduce the effect of fluctuating hearing levels on the results, children with evidence of middle ear abnormality were excluded. Each of the subjects included in the analysis showed normal multiple probe tone tympanometric results on each of the test occasions and no significant air-bone gap at any test frequency on the occasion of their behavioral hearing assessment.

Results from 575 infants and young children (1091 ears) were included in the analysis. ASSR thresholds at a range of test frequencies were established in each of these subjects between the (corrected) ages of 0.5 and 3 months (mean: 2.6 months). ASSR testing was performed in sound-treated rooms with the child in natural sleep. Electroencephalographic activity was measured using either Nikomed or Neuroline neonatal electrodes. Differential recordings were made between electrodes placed on the high forehead (Fz) or vertex (Cz) and the ipsilateral mastoid or earlobe. A third electrode placed on either the low forehead or contralateral mastoid served as a ground. Interelectrode impedance was minimized using abrasive skin preparation materials, and was typically ≤5kΩ at 260 Hz. Data was excluded if impedance values exceeded 10 kΩ.

The test stimuli were single 500 Hz, 1 kHz, 2 kHz, and 4 kHz tones amplitude and frequency modulated at rates between 74 Hz and 95 Hz. This modulation range was used to avoid the problems associated with ASSR testing at lower rates (<70 Hz) in sleeping pediatric subjects (Levi et al., 1993). Amplitude modulation (depth 100%) and frequency modulation (width 10% of the carrier tone) were combined to maximize response amplitude (Rickards et al., 1994).

Auditory steady-state response analysis was carried out in the manner described by Cohen et al. (1991). The raw electroencephalogram was passed through a preamplifier, bandpass filtered (10 Hz–500 Hz), and then Fourier analyzed at the stimulus modulation frequency to extract response phase and amplitude information. The presence or absence of a response was then determined automatically with a statistical detection criterion based on nonrandom phase behavior (phase coherence).
established, further testing in 5 dB steps was carried out. The threshold was defined as the softest level at which the phase coherence was statistically significant at the p < 0.03 level. Where possible, thresholds were established at the four carrier frequencies in each ear. This assessment typically required a test time of between 30 and 45 minutes. As the testing was carried out with the subject in natural sleep, it was not always possible to obtain a complete data set.

Behavioral hearing threshold levels were established using age-appropriate (visual response audiometry) assessment techniques in sound-treated test rooms. The corrected age of the subjects at the time of the testing ranged from 6 months to 23 months (mean: 9.8 months). These assessments were carried out by experienced pediatric audiologists, and results were only included in the analysis if they were considered to be reliable. The test stimuli were warble tones at octave frequencies from 500 Hz to 4 kHz and were presented monaurally via headphones or tubephones. The maximum presentation level was 120 dBHL for all frequencies.

**RESULTS**

**Normal-Hearing Subjects**

Two hundred and eighty-five of the subjects who underwent ASSR evaluation in infancy subsequently showed behavioral hearing thresholds within the normal audiometric range (i.e., conditioned hearing thresholds ≤15 dBHL). The mean and standard deviation of the ASSR thresholds obtained at each test frequency in these children is shown in Table 1. Mean ASSR threshold levels ranged from 24.3 dBHL to 32.5 dBHL. In addition, Table 1 shows the ASSR/behavioral hearing threshold difference levels for each ear at each carrier frequency. (Difference values were determined by subtracting the behavioral hearing threshold from the ASSR threshold at each test frequency). In this case the mean difference values for the various carrier tones ranged from 22.4 dB to 31.0 dB.

The stimulus sensation level required to elicit the ASSR varied with carrier frequency in this group of normally hearing infants. Analysis of variance showed a significant difference across test frequencies (F = 87.15; p < 0.001), and post hoc analysis revealed that while the ASSR/behavioral hearing threshold differences at the 500 Hz and 1 kHz test frequencies were not different from each other, the threshold difference levels at these frequencies were significantly higher than those obtained at both the 2 kHz and 4 kHz test frequencies (p < 0.05). Furthermore, ASSR thresholds at 4 kHz were obtained at significantly higher sensation levels than those at the 2 kHz test frequency (p < 0.05).

**Results for Subjects with Sensorineural Hearing Loss**

Two hundred and seventy-one of the children evaluated in this study were shown to have sensorineural-type hearing loss in one or both ears. Results for these children were combined with those of the normally hearing group and were subjected to correlation and regression analysis. Overall, the findings showed a strong correlation between ASSR threshold and behavioral hearing threshold levels. Pearson r correlation coefficient values ranged from 0.96 to 0.98 across the test frequencies (Table 2).

Figure 1 shows the distribution of ASSR/behavioral hearing threshold comparisons for all of the normally hearing and sensorineural hearing loss subjects at each of the test frequencies. Two thousand nine hundred and forty-three comparisons were included in the analysis: 715 at 500 Hz, 692

<table>
<thead>
<tr>
<th>Table 1. ASSR Threshold Levels and ASSR/Behavioral Threshold Difference Levels for Normally Hearing Subjects at Each of the Test Frequencies</th>
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<tbody>
<tr>
<td><strong>Test Frequency</strong></td>
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<tr>
<td>-------------------</td>
</tr>
<tr>
<td><strong>ASSR Threshold</strong></td>
</tr>
<tr>
<td>Mean (dB)</td>
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<tr>
<td>Std Dev (dB)</td>
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<tr>
<td><strong>Difference Level</strong></td>
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<tr>
<td>Mean (dB)</td>
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<tr>
<td>Std Dev (dB)</td>
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</tbody>
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ASSR thresholds in the sensorineural hearing loss subjects were typically obtained at levels slightly higher than the behavioral hearing levels. How much higher was related to the degree of the child's loss. This finding is reflected in the linear regression lines that have been fit to the data for the various carrier frequencies. In each case the slope of less than unity indicates that ASSR thresholds tended to be closer to hearing threshold as the degree of hearing loss increased.

Of the five hundred and fifty-six subjects with either normal hearing or sensorineural hearing loss, only four showed ASSR thresholds at levels >10 dB lower than their subsequently established behavioral thresholds. In each of these cases, there was evidence of significant deterioration in hearing level in the time between the ASSR and behavioral hearing assessments. Repeat ASSR evaluation in each instance showed results that corresponded with the audiogram. Results for these children were not included in the statistical analysis and are

### Table 2. Pearson Product Moment Correlation Coefficient Values Comparing ASSR and Behavioral Hearing Thresholds

<table>
<thead>
<tr>
<th>Test Frequency</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal/Sensorineural Group</td>
<td>0.96</td>
<td>0.97</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Auditory Neuropathy Group</td>
<td>0.54</td>
<td>0.49</td>
<td>0.55</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Figure 1. Distribution of ASSR/behavioral hearing threshold comparisons for ears with normal hearing or sensorineural-type hearing loss. Dashed lines represent 1:1 ASSR-behavioral correspondence. The solid lines are the linear regression lines. The regression formula for each frequency is shown.
Figure 2. ASSR and behavioral audiograms for a child with sensorineural hearing loss following viral meningitis. (A) ASSR thresholds at two months of age (18 days post infection). (B) Conditioned audiometric thresholds obtained at six months of age (ASSR thresholds at two months). (C) ASSR and behavioral hearing thresholds obtained at ninth months of age. (D) ASSR and behavioral hearing thresholds at 26 months of age.

represented by filled circles in Figure 1.

Case Study

Figure 2 shows examples typical of the way in which ASSR thresholds mirrored the behavioral audiogram in the babies with sensorineural hearing loss assessed in this study. Audiograms A-D track the partial hearing recovery that occurred over a 12-month period in a young subject who suffered a bout of viral meningitis at one month of age. The repeat assessments in this example reflect the changing degree and configuration of the hearing loss and show the utility of the ASSR procedure for the evaluation of ears with only minimal amounts of residual hearing.

Auditory Neuropathy Subjects

Nineteen of the children evaluated in this study presented with auditory neuropathy (AN)-type hearing loss. Auditory neuropathy is a disorder in which cochlear amplification (outer hair cell) function is normal but afferent neural conduction in the auditory pathway is disrupted (Starr et al, 1996). Each of the auditory neuropathy subjects fit the typical clinical AN pattern in that they showed absent auditory brainstem responses (ABRs) to acoustic clicks at maximum presentation levels but had present outer hair cell responses including otoacoustic emissions and cochlear microphonics (Rance et al, 1999).

The distribution of ASSR/behavioral
The mean ASSR threshold sensation levels for normally hearing babies in this study were in the range 22 to 30 dBHL. This result is consistent with previously reported findings for infant subjects. Lins et al (1996) used a “4-carrier frequency” combined ASSR technique to determine response threshold in a group of (presumed normal) subjects with a similar age range (1–10 months), and also found mean ASSR thresholds of around 20–30 dBHL. As in the present study, the Lins et al (1996) data also showed a significant effect of carrier frequency with ASSR thresholds obtained at significantly lower levels for high-frequency stimuli than for low frequencies. This pattern can also be seen in the findings of a large-scale study of ASSR thresholds in newborn subjects reported by Rickards et al (1994) where the mean response threshold at 500 Hz was approximately 10 dB higher than those obtained for stimuli in the high-frequency range. The high-frequency advantage reported in these studies is consistent with the findings of Cohen et al (1991) that high-frequency tones elicit comparatively larger ASSR amplitudes in sleeping subjects and may reflect the greater neural synchronization of responses from the basal cochlear turn.

The ASSR threshold levels obtained for the 0.5- to 3-month-old subjects in this study were lower than those reported previously for normal neonates. Rickards et al (1994) used
similar test parameters and procedures to those of the present study and found higher mean ASSR threshold levels at each of the common test frequencies. The difference in ASSR threshold between the studies was particularly evident for the 500 Hz test frequency where thresholds obtained in the newborns were typically 10 dB higher than those obtained for the slightly older infants described in this paper. While the effect of extraneous factors such as the fluctuating middle ear status of the neonates and test environment differences cannot be discounted, the findings do point to developmental changes in ASSR threshold occurring in the first weeks of life.

Overall, the ASSR thresholds for the normally hearing cohort in this investigation were significantly higher than those reported for the tone-burst auditory brainstem response (TB-ABR) technique. Assessment using toneburst ABR is currently the best alternative to the ASSR procedure for frequency specific assessment of hearing in young children. Mean toneburst ABR thresholds have been obtained in both neonatal (Sininger et al, 1997) and infant (Stapells et al, 1995) subjects at levels 10–20 dB lower than seen for ASSR testing in this study. Why the discrepancy between these two auditory brainstem-based electrophysiological techniques should occur is a matter for further investigation. What is clear is that ASSR testing (as carried out in this study) cannot reliably differentiate between normal ears and those with mildly elevated hearing levels. The accuracy of the technique does, however, improve dramatically in ears with sensorineural hearing loss.

For the children with sensorineural hearing loss in this study, there was a strong relationship between the ASSR thresholds obtained in infancy and their subsequently established audiograms. The results described in Figure 2 are typical of those obtained in this subject group with the ASSR threshold pattern reflecting both the degree and configuration of the hearing loss. The audiograms shown in Figure 2 also reflect one of the particular advantages of ASSR assessment in subjects with only minimal amounts of residual hearing. The continuous tones used to elicit the ASSR resemble the stimuli used in clinical behavioral testing and can be presented at higher levels than is possible for brief stimuli such as acoustic clicks or tone bursts. (Brief stimuli require a calibration correction to account for temporal summation differences between short- and long-duration signals). As such, the ASSR technique is well suited to quantification of hearing loss in the severe to profound range.

Overall, the results of this study are consistent with those reported previously for infants and young children with sensorineural hearing loss (Rance et al, 1995, 1998; Lins et al, 1996; Aoyagi et al, 1999; Rance and Briggs, 2002; Rance and Rickards, 2002; Vander Werff et al, 2002; Stueve and O’Rourke, 2003; Swanepoel et al, 2004) and indicate that ASSR testing in the first few months of life can offer information accurate enough to form a basis for hearing aid fitting and early intervention.

The results obtained for subjects with auditory neuropathy-type hearing loss, in contrast, indicate that the ASSR technique in such cases cannot be used to predict the behavioral audiogram. That the typical ASSR/behavioral hearing threshold relationship should be disrupted in these children is not surprising. Any attempt to estimate hearing levels on the basis of evoked potential findings (ASSR or otherwise) is based on the assumption that the subject’s auditory pathway is normal and that an elevation in response threshold reflects a reduction in the sensitivity of the peripheral (middle ear/cochlear) hearing mechanism. In the case of auditory neuropathy, this assumption is violated as affected subjects show evidence of normal cochlear (outer hair cell) function but disordered neural conduction through the auditory pathway (Starr et al, 1996). The results obtained in this study are consistent with those reported previously (Rance et al, 1999; Rance and Briggs, 2002) and indicate that evoked potentials arising in the auditory brainstem/midbrain (such as the ASSR to high rate stimuli) are severely affected in cases of auditory neuropathy and cannot be used to predict hearing levels.

Clearly, interpretation of elevated ASSR thresholds requires an understanding of the type of hearing loss affecting the subject. ASSR testing, which involves assessment in the frequency domain, cannot differentiate between peripheral (cochlear) hearing losses and those that are related to neural transmission or retrocochlear abnormalities.
As such, it is clinically important (particularly in neonatal intensive care unit [NICU] graduates who make up a high proportion of pediatric cases with auditory pathway disorders) to consider ASSR findings in conjunction with the results of other measures of auditory system function such as otoacoustic emissions, cochlear microphonics, and behavioral observation (Rance et al, 1999; Cone-Wesson, Parker, et al, 2002).

**SUMMARY**

Establishment of universal hearing screening programs around the world has allowed identification of impaired children in the neonatal period. The results of this clinical study indicate that ASSR assessment can offer a useful next step in the evaluation process for these early-identified youngsters, in most cases allowing the behavioral audiogram to be predicted and intervention processes to be implemented.

**NOTES**

1. The participating audiology centers were the University of Melbourne, School of Audiology Clinic; Ballarat Hearing Centre; Taralyle—The Oral Language Centre for Deaf Children; Royal Children’s Hospital (Melbourne); Monash Medical Centre; Geelong Hospital; and the Shepparton Hearing Centre.

2. Modulation rate varied with carrier frequency as follows: the 500 Hz carrier was modulated at 74 Hz, the 1 kHz carrier at 81 Hz, the 2 kHz carrier at 88 Hz, and the 4 kHz carrier at 95 Hz.

3. The etiologies of these subjects were consistent with deteriorating hearing. Two of the children had Enlarged Vestibular Aqueduct Disorder; one child’s loss was considered to be related to CMV exposure in utero; and one child had Pendred’s Syndrome.

**REFERENCES**


