Auditory Steady-State Responses for Children With Severe to Profound Hearing Loss

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Objective: To investigate the clinical usefulness of the dichotic single-frequency auditory steady-state response (ASSR) for estimation of behavioral thresholds in children with severe to profound congenital sensorineural hearing loss.

Design: A comparative experimental research design was selected to compare behavioral and ASSR thresholds for the sample. Behavioral pure-tone audiometry served as the criterion standard.

Setting: Hearing Clinic, Department of Communication Pathology, University of Pretoria, Pretoria, South Africa.

Patients: A referred sample of 10 patients (20 ears), 5 girls and 5 boys aged 10 to 15 years (mean age, 13 years 4 months), with severe to profound sensorineural hearing impairment.

Main Outcome Measures: The difference, and correlation, between 160 pure-tone behavioral and ASSR thresholds at 0.5, 1, 2, and 4 kHz.

Results: Mean differences between ASSR and behavioral thresholds were 6 dB for 0.5 kHz and 4 dB for 1, 2, and 4 kHz, with standard deviations varying between 8 and 12 dB. No significant differences (P<.05) were observed between ASSR and behavioral thresholds, except at 0.5 kHz, and Pearson correlation coefficients varied between 0.58 and 0.74 across the evaluated frequencies, with best correlation at 1 kHz and worst at 0.5 kHz.

Conclusions: The ASSR thresholds provided reliable estimations of behavioral thresholds for children with severe to profound hearing loss and indicated an increased sensitivity for more profound hearing loss.

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delineate thresholds up to 120 dB HL, whereas the ABR was insensitive to threshold variations within the severe to profound hearing loss range. In a more recent summary of clinical results, Rance and Briggs reported the specific usefulness of the ASSR to acquire accurate thresholds at profound levels (>90 dB HL [hearing level]). Absence of ASSR thresholds was always indicative of profound levels of hearing loss, with 93% of behavioral thresholds at levels of 115 dB HL or greater in these instances.7

A preliminary study recently reported by Swane-poel and Hugo investigated ASSR threshold results in a sample of young (10-60 months) cochlear implant candidates compared with behavioral free-field and click ABR thresholds. Behavioral and ABR thresholds were obtained only in a single case in a cohort of 13 infants. This was also the only subject with a severe hearing loss; all other subjects had profound hearing losses. The ASSR thresholds were measured in 89 (74%) of the 120 frequencies evaluated and were at least 5 dB higher than the maximum output of the free-field audiometric procedure in 79% of the frequencies assessed. Almost all (92%) of the ASSR thresholds were obtained at intensities higher than the maximum ABR output. The ASSR was the only technique that provided threshold information regarding residual hearing in 93% of the ears assessed.

The ASSR evaluations at these high intensities present 2 distinct advantages over techniques like the ABR. First, ASSR thresholds at these elevated intensities allows for a more accurate hearing aid fitting, and second, the absence of an ASSR threshold at maximum intensities is indicative of unusable hearing, which predicts poor hearing aid results. This information can assist in the decision-making process for cochlear implant candidacy, especially in very young patients for whom objective threshold-determining procedures are becoming the primary candidacy criterion. According to Picton and colleagues, the ASSR technique is ready for clinical use in the field of objective audiometry, although there remains much to be done. The exact relationship between behavioral and physiologic thresholds at such high intensities is not yet clear and requires cautious investigation. This study presents the results of an investigation for determining severe to profound hearing loss in a sample of children with the use of a dichotic single-frequency ASSR technique compared with behavioral pure-tone audiometry.

METHODS

The institutional review board at the University of Pretoria (Pretoria, South Africa) approved this project.

SUBJECTS

A sample of 10 subjects (20 ears), 5 girls and 5 boys, with severe to profound congenital sensorineural hearing loss were studied. All subjects were between the ages of 10 and 15 years, with a mean age of 13 years 4 months. According to the pure-tone average (PTA) across 0.5, 1, and 2 kHz, 10 ears were classified as having profound hearing impairment (PTA >90 dB HL) and 10 were classified as having severe hearing impairment (PTA, 71-90 dB HL). All subjects underwent an audiologic test battery, including otoscopy, tympanometry, and behavioral audiometry, before ASSRs were measured. Normal middle-ear compliance was a prerequisite for including any subject. Subjects were requested to sleep or relax on a bed with closed eyes during the ASSR assessment.

STIMULI

Behavioral thresholds were determined with pure tones at 0.5, 1, 2, and 4 kHz presented through TDH 39 supra-aural earphones. The ASSRs were evoked by means of a dichotic single-frequency technique stimulating both ears simultaneously with the same carrier frequency modulated at different rates. A single frequency per ear was evaluated because all subjects had severe to profound hearing losses, and possible interactions between multiple stimuli at intensity levels above 60 dB sound pressure level may contaminate the accuracy of responses.

Test stimuli were 0.5-, 1-, 2-, and 4-kHz tones modulated in amplitude and frequency with a relative amplitude modulation–frequency modulation phase difference of 90°. The tones were 20% frequency modulated and 100% amplitude modulated at 65 Hz for all tones in the left ear and 69 Hz for tones in the right ear according to the default specifications of the ASSR system (Navigator Pro MASTER; Bio-Logic Systems Corp, Mundelein, Ill). Modulation rates in excess of 65 Hz were used to ensure that a satisfactory signal-to-noise ratio would exist for detection of responses during sleep or sedation. Test stimuli were presented through insert earphones calibrated in hearing level. The stimuli were separately calibrated for each frequency by means of pure tones according to the AS 1991.2 standard. All measurements were made with a sound level meter (model Investigator 2260; Bruel & Kjaer, Norcross, Ga), an artificial ear type 4132 and a microphone type 4144. The maximum intensity for stimulation was approximately 120 dB HL for all test frequencies used (0.5, 1, 2, and 4 kHz).

RECORDINGS

All behavioral and ASSR recordings were obtained in a single-walled sound booth within a sound-treated room. For behavioral audiometry, pure-tone behavioral thresholds were obtained by means of a clinical audiometer (GSI 61; Grason-Stadler, Madison, Wis) to present the tones in a 10-dB-down and 5-dB-up threshold-seeking procedure.

The ASSR assessments were performed by a dichotic single-frequency technique. This implies that a single frequency was evaluated in both ears simultaneously. This type of simultaneous stimulation has proven to be a time-efficient way of determining ASSR thresholds.13-16 Recordings commenced with a 1-kHz carrier frequency presented dichotically, followed by 0.5, 2, and 4 kHz. Electrode disks of silver–silver chloride were fixed with electrolytic paste to the scalp at position Cz (active), midline posterior neck (reference), and Fpz (ground). All electrode impedances were below 5 kΩ at 10 Hz, and the interelectrode impedance values were kept below 3 kΩ. The bioelectric activity was amplified and analog filtered by means of a filter bandpass of 3 to 300 Hz. A maximum of 20 sweeps containing 16 epochs each was recorded per trial. Each epoch was 1.024 seconds, and a complete sweep lasted 16.384 seconds. The electrophysiologic recording was converted by means of a fast Fourier transform after each sweep. The presence of a response was determined with an F ratio comparing the fast Fourier components at the stimulus modulation frequencies with the 120 adjacent frequencies (60 bins above and 60 bins below the frequency) to determine whether the difference was significantly different (P < .05) from the background noise. If a sweep contained more than 80 nV of electrophysiologic noise, it was rejected. A recording was halted once a preset probability of 95% response significance was achieved after averaging at least 5 sweeps, or when a statistically significant probability...
Mean Behavioral Thresholds and ASSR Estimates for the Whole Sample and for Severe and Profound Thresholds

<table>
<thead>
<tr>
<th>Thresholds</th>
<th>0.5-kHz Stimulus</th>
<th>1-kHz Stimulus</th>
<th>2-kHz Stimulus</th>
<th>4-kHz Stimulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>No. of Thresholds</td>
<td>Mean ± SD</td>
<td>No. of Thresholds</td>
</tr>
<tr>
<td>All</td>
<td>Behavioral</td>
<td>84 ± 13</td>
<td>20</td>
<td>92 ± 12</td>
</tr>
<tr>
<td></td>
<td>ASSR</td>
<td>91 ± 8</td>
<td>20</td>
<td>95 ± 8</td>
</tr>
<tr>
<td></td>
<td>Difference score</td>
<td>6 ± 6</td>
<td>20</td>
<td>4 ± 8</td>
</tr>
<tr>
<td>Severe</td>
<td>Behavioral</td>
<td>78 ± 12</td>
<td>12</td>
<td>80 ± 10</td>
</tr>
<tr>
<td></td>
<td>ASSR</td>
<td>89 ± 10</td>
<td>12</td>
<td>89 ± 8</td>
</tr>
<tr>
<td></td>
<td>Difference score</td>
<td>10 ± 6</td>
<td>12</td>
<td>6 ± 6</td>
</tr>
<tr>
<td>Profound</td>
<td>Behavioral</td>
<td>97 ± 4</td>
<td>7</td>
<td>99 ± 5</td>
</tr>
<tr>
<td></td>
<td>ASSR</td>
<td>94 ± 6</td>
<td>7</td>
<td>99 ± 6</td>
</tr>
<tr>
<td></td>
<td>Difference score</td>
<td>-4 ± 7</td>
<td>7</td>
<td>0 ± 7</td>
</tr>
</tbody>
</table>

Abbreviation: ASSR, auditory steady-state response.

*Severe and profound thresholds were classified according to the behavioral thresholds obtained (severe, 71-90 dB; profound, >90 dB).

value could not be achieved within 20 sweeps (327.68 seconds). A 10-dB-down and 5-dB-up threshold-seeking procedure was used up to a maximum stimulation level of 120 dB HL. The initial stimulation intensity was based on the behavioral thresholds obtained and usually commenced 20 dB above the behavioral threshold of the worst ear. If a significant response was not obtained in both ears at this intensity, the intensity was increased until a significant response was obtained in both ears. Once a significant response was obtained for both ears, the intensity was lowered to obtain a threshold in both ears. Threshold was taken as the lowest intensity such that a response was found at that level but no response was found at a level lower.

Pure-tone behavioral and ASSR thresholds were obtained for all frequencies evaluated. The Table gives the mean thresholds for both procedures as obtained from 80 measurements per assessment procedure (4 frequencies × 20 ears). The mean behavioral thresholds for the entire sample varied between 84 and 93 dB HL, compared with mean ASSR thresholds between 91 and 96 dB HL. The mean difference between ASSR and behavioral thresholds was 6 dB for 0.5 kHz and 4 dB for 1, 2, and 4 kHz, with standard deviations varying between 8 and 12 dB. The ASSR and behavioral threshold differences for all measurements were within 0 to 10 dB of the pure-tone threshold in 69% of recordings and within 15 dB in 23% of recordings, and only 8% of thresholds differed by 20 dB, which was the maximum difference in thresholds. The severe (PTA, 71-90 dB HL) and profound (PTA, >90 dB HL) behavioral thresholds across the various frequencies were separated and compared with the ASSR estimations. The resultant mean thresholds and standard deviations of each procedure are presented in the Table. The results indicate better ASSR threshold estimations for the profound thresholds at all frequencies. The ASSR thresholds for the profound group, however, overestimated the behavioral thresholds, on average, at all frequencies except for 1 kHz, where it corresponded exactly with the mean behavioral threshold. Of the 36 ASSR thresholds estimating profound behavioral thresholds, 19 (53%) underestimated the behavioral audiogram. The ASSR thresholds estimating profound behavioral thresholds were, on average, within 1 to 4 dB except for 4 kHz, where the ASSR underestimated behavioral thresholds by 7 dB. In the case of the severe thresholds, the ASSR overestimated the behavioral thresholds in all instances, differing on average by 6 to 13 dB from behavioral thresholds.

The close approximation of behavioral thresholds by the ASSR was improved by the fact that 19 (24%) of the 80 ASSR measurements were recorded below pure-tone thresholds. All of these underestimated ASSR thresholds were recorded in the case of profound behavioral thresholds (>90 dB HL). In 5 ears, 2 or more ASSR thresholds were obtained below the behavioral threshold. Fourteen (74%) of the 19 ASSR thresholds recorded below the corresponding behavioral thresholds differed by 10 dB or less, and only in 2 instances was a difference of 20 dB recorded. This underestimation of the pure-tone audiogram leads to an improved mean threshold comparison of the ASSR with behavioral thresholds.

Figure 1 and Figure 2 show the frequency distribution of the obtained behavioral and ASSR thresholds. The majority (55%) of behavioral thresholds were recorded at 80 to 95 dB HL, and 0.5 kHz was the only frequency presenting with thresholds between 60 and 65 dB. The ASSR demonstrated a majority concentration (73%) of recorded thresholds between 90 and 100 dB HL across frequencies. A smaller range of recorded thresholds (70-105 dB) was observed for the ASSR than for behavioral thresholds (60-120 dB).

Pearson correlation coefficients were calculated to assess the relationship between ASSR and behavioral thresholds at each frequency. Figure 3 presents the results according to the different frequencies. Correlation was established for the test measures at 0.38 to 0.74 across the evaluated frequencies. The best correlation was obtained at 1 kHz (0.74), and the worst correlation coefficient was obtained at 0.5 kHz (0.38). When ASSR thresholds that overestimated the behavioral thresholds (19/80) were omitted, the correlation coefficients increased significantly to 0.85, 0.89, 0.81, and 0.69 for 0.5, 1, 2, and 4 kHz, respectively. According to a P<.05 test, there...
ment associated with hearing impairment.4 This means severe degrees of hearing loss may be related to recruitment. This increased sensitivity of the ASSR to more severe degrees of hearing loss typical of patients considered for cochlear implantation and comparable with that in young infants with severe to profound hearing loss and the best correlation were obtained for 1 kHz. The largest mean difference between ASSR and behavioral thresholds was evident at 0.5 kHz, and it was also the only frequency indicating a statistically significant difference (P<.05) between ASSR and behavioral thresholds. Problems in estimating 0.5-kHz ASSR thresholds have been reported previously2,5 and, according to Lins and colleagues,4 could result from the fact that the low-frequency–evoked response has a greater intrinsic jitter, due to neural asynchrony, which could cause the relative difficulty of threshold estimation compared with higher test frequencies. According to Herdman and Stadig,21 another reason may be that stimulus protocols for amplitude-modulated tones at 0.5 kHz are not yet optimal. This phenomenon requires further investigation at these high stimulation intensities, especially because caution must be used when stimulation is performed at high intensities for prolonged periods.3

Obtaining threshold information at these elevated intensities is becoming increasingly relevant in light of the reduction in age of patients undergoing cochlear implantation and the inability of other electrophysiologic procedures, such as the ABR,2,3 to assess residual hearing at these high intensities. These populations of infants and young children with profound hearing loss are often unable to respond to behavioral test techniques and rely primarily on electrophysiologic techniques.2,21 If the hearing aids for a child with a profound hearing loss were not set at an optimal level according to actual threshold results, the child may not have had a “true” hearing aid trial (to observe performance when making optimal use of residual hearing).9 Previously, hearing aid fittings for these infants and young children were based solely on absent ABR thresholds, and thus ASSR thresholds can assist the initial hearing aid fitting with actual thresholds. Furthermore, absent ASSR thresholds indicate no usable hearing, whereas absent ABR thresholds are not. Because the ASSR allows for better hearing aid fittings, resulting in true hearing aid trials, and absent ASSR thresholds predict poor hearing aid benefit, the ASSR is uniquely suited, above the ABR, to assist in the assessment of young children for cochlear implantation.

In conclusion, this study indicated that the dichotomic single-frequency ASSR technique provides reliable estimations of behavioral hearing thresholds for children presenting with severe to profound hearing loss and demonstrated an increased sensitivity for profound hearing impairments. Accuracy of the ASSR for adults and older children with severe to profound hearing loss is similar and comparable with that in young infants with severe to profound hearing loss.22 This allows the advantages of ASSR demonstrated in this study to be generalized to young infants being considered for cochlear implantation. The ASSR may be the only procedure able to accurately characterize residual hearing for profound hearing impairment in infants and young children who are

The results of this study show that ASSR thresholds can be obtained reliably at various frequencies for children with severe to profound hearing loss. The majority of ASSR thresholds (69%) were recorded between 0 and 10 dB from the corresponding behavioral thresholds, and the largest deviation from behavioral thresholds was 20 dB (6/80). The results indicate a closer correlation between ASSR and profound behavioral thresholds than for severe thresholds. All ASSR thresholds that overestimated behavioral thresholds (19/80) were estimating profound behavioral hearing levels. These improved correlations for more profound degrees of hearing loss are in agreement with the general trend in previous studies,2,13,19 which indicate that the ASSR was most accurate in estimating behavioral thresholds for more severe degrees of hearing loss typical of patients considered for cochlear implantation. This increased sensitivity of the ASSR to more severe degrees of hearing loss may be related to recruitment associated with hearing impairment.7 This means that physiologic thresholds are higher than behavioral thresholds at low intensity and come closer to the behavioral thresholds at high intensity. The threshold differences for the current study compared favorably with differences between data reported in other studies investigat-
unable to provide reliable behavioral responses. This type of threshold information is important to a process of accountable hearing aid selection and fitting, and ultimately also to assessment of cochlear implant candidacy for young infants.

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## REFERENCES