The Clinical Value of the Multiple-Frequency 80-Hz Auditory Steady-State Response in Adults With Normal Hearing and Hearing Loss

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Objectives: To determine the ability of the air-conduction multiple-frequency auditory steady-state response (ASSR) technique to diagnose normal hearing (NH) and mild and moderate degrees of sensorineural hearing loss (SNHL), to assess patients with conductive hearing loss (CHL), to evaluate flat and sloping configurations of hearing impairment, and to provide sensitivity and specificity values for various ASSR cutoff criteria.

Design: A comparative study between ASSR and criterion-standard behavioral thresholds.

Setting: Ear, nose, and throat department at a university hospital.

Patients: The study population comprised 40 adults with NH, 17 with SNHL, and 7 with CHL.

Main Outcome Measures: The measure of interest was the difference between ASSR and behavioral thresholds at 0.5, 1.0, 2.0, and 4.0 kHz. The sensitivity, specificity, positive predictive value, negative predictive value, and efficiency were calculated for several ASSR cutoff criteria.

Results: The ASSR technique clearly distinguished moderate SNHL from NH, but the “mild SNHL and NH” and “mild SNHL and moderate SNHL” differentiation was particularly difficult at 0.5 and 2.0 kHz, respectively. Air-conduction ASSR thresholds accurately predicted behavioral thresholds in CHL. The ASSR system precisely reflected the flat and sloping configurations. Finally, the most appropriate ASSR cutoff point for normality seems to be the 30-dB-or-lower criterion.

Conclusions: In adults, the multiple-frequency 80-Hz ASSR technique can be used to determine the degree and configuration of hearing loss. Although air-conduction ASSR thresholds accurately predicted behavioral thresholds in CHL, future research with bone-conduction ASSRs is necessary to establish the type of hearing loss. Furthermore, the applicability of these findings still needs to be confirmed for infants.


The implementation of universal newborn hearing screening programs has decreased the age of identification of hearing loss to the first few weeks of life. Accordingly, pediatric audiologists are challenged with performing diagnostic hearing assessments in very young infants who cannot provide reliable behavioral results. Considering that appropriate intervention strategies should be initiated before 6 months of age to be beneficial for speech and language development, audiologists must rely on objective procedures such as acoustic immittance measures, otoacoustic emissions, and auditory-evoked potential techniques. This objective test battery aims at accurately determining the degree, type, and configuration of hearing loss.

The click auditory brainstem response (ABR) is clinically the most widely used auditory-evoked potential for predicting behavioral thresholds. Unfortunately, ABR thresholds to clicks cannot provide frequency-specific information, correlating mainly with the best or the average pure-tone behavioral thresholds in the 1000- to 4000-Hz range. Frequency-specific thresholds can be obtained using ABR in response to tone-burst stimuli. However, the tone-burst ABR has 2 major shortcomings: (1) the accuracy of threshold estimation depends on the experience and skill of the audiologist owing to the subjective visual inspection method used to judge the presence or absence of tone-burst ABRs; and (2) it is a time-consuming procedure of threshold determination because only 1 ear and 1 frequency can be evaluated at a time. In addition, both the click and tone-burst ABR are limited in the highest stimulation level (depending on the ABR equipment: 90-
An alternative frequency-specific auditory-evoked potential is the auditory steady-state response (ASSR) technique, which offers several attractive features for clinical application including objective detection algorithms, multiple-frequency stimulation, and higher stimulation levels. Especially, the ASSR to stimuli modulated at rates in the 70- to 110-Hz range (the “80-Hz ASSR”) has been gaining popularity because of its suitability in assessing sleeping or sedated infants and young children. Several investigations have demonstrated that this 80-Hz ASSR method accurately estimates the degree and configuration of the behavioral audiogram in both adult and pediatric subjects. In addition, the degree of hearing impairment considerably affects the ASSR threshold accuracy. ASSR thresholds are closer to behavioral thresholds for patients with sensorineural hearing loss (SNHL) compared with subjects with normal hearing (NH), and in patients with SNHL, the difference between ASSR and behavioral thresholds decreases as the severity of hearing loss increases. This phenomenon has been attributed to “physiological recruitment,” which occurs in patients with SNHL. Although 80-Hz ASSR threshold results have been presented separately for moderate and profound degrees of SNHL, to our knowledge, none of the published research has specifically reported ASSR threshold results for mild SNHL. Nevertheless, ASSR regression formulae developed by the Melbourne group to predict behavioral thresholds for the single-frequency GSI Audera system (VIASYS NeuroCare, Madison, Wisconsin) already suggest that difficulties may arise in differentiating NH and mild and moderate degrees of SNHL. Therefore, additional research is required to establish normative air-conduction as well as bone-conduction ASSR thresholds, not only for subjects with NH and SNHL but also for patients with actual conductive or mixed hearing loss.

Considering the type of hearing loss, most investigations have focused on SNHL, with, to our knowledge, no published studies of air-conduction ASSR thresholds in patients with actual conductive or mixed hearing loss. Two studies have recorded ASSRs in adults with simulated conductive hearing loss (CHL), which resulted in larger differences between ASSR and behavioral thresholds compared with patients with SNHL. Furthermore, only 1 study reported 2 cases of children with bilateral severe to profound SNHL and transient middle ear dysfunction, which produced significant deteriorations of the ASSR threshold levels. To be used as a standard diagnostic clinical instrument, ASSR systems need to establish normative air-conduction as well as bone-conduction ASSR thresholds, not only for subjects with NH and SNHL but also for patients with actual conductive and mixed hearing loss.

The aim of the present study was to evaluate the clinical value of the air-conduction multiple-frequency ASSR approach in adults with NH, SNHL, and CHL. First, the precision of ASSR threshold estimations was investigated for NH and mild and moderate degrees of SNHL. Second, the impact of CHL on ASSR threshold measurements was considered. Third, the effect of configuration of hearing loss on ASSR threshold accuracy was evaluated for flat and sloping SNHL. Finally, the effectiveness of the multiple-frequency 80-Hz ASSR technique was evaluated by calculating its sensitivity, specificity, positive and negative predictive values, and efficiency for various ASSR cutoff criteria.

**PARTICIPANTS**
A total of 64 adults (32 women) aged between 18 and 60 years participated in this study. Each participant received an audiological evaluation including otoscopy, pure-tone audiometry, 226-Hz tympanometry, and ipsilateral acoustic reflexes at 0.5, 1.0, and 2.0 kHz. Pure-tone thresholds by air conduction were established for each octave frequency from 0.25 to 8.0 kHz and by bone conduction from 0.5 to 4.0 kHz using the modified Hughson-Westlake procedure. Accordingly, the following 3 groups of subjects could be distinguished (Table 1): (1) an NH group that comprised 40 adults (20 women; mean age, 22 years [range, 18-32 years]); (2) an SNHL group that comprised 17 subjects (8 women; mean age, 47 years [range, 19-60 years]) with symmetrical hearing loss; and (3) a CHL group that comprised 7 adults (4 women; mean age, 36 years [range, 25-54 years]) with unilateral (n=6) and bilateral (n=1) hearing impairments. This investigation was approved by the ethics committee at the University Hospital of Ghent, Ghent, Belgium. All subjects read and signed an informed consent.

**ASSR STIMULI**

The Multiple Auditory Steady-State Response (MASTER) software (version 2.02) running on the Bio-logic Navigator Pro AEP system (Natus Medical Incorporated, San Carlos, California) was used for the ASSR measurements. The air-conducted stimuli were a combination of 100%-exponentially amplitude-modulated (AM²) and 20%-frequency-modulated (FM) tones (AM²/FM), which were presented through Etymotic ER-3 insert earphones (Etymotic Research Inc, Elk Grove Village, Illinois). No bone-conduction stimuli were presented. The carrier frequencies of interest were 0.5, 1.0, 2.0, and 4.0 kHz and depending on the test situation, the following 3 stimulus conditions could be used:

1. Dichotic multiple: 8 AM²/FM tones were presented simultaneously (4 to each ear) when subjects had NH, SNHL, or bilateral CHL. The modulation frequencies were 82.031, 90.234, 98.437, and 105.469 Hz, for the left ear and 85.547, 93.750, 103.125, and 110.156 Hz for the right ear.

2. Monotic multiple: only the left or right ear was investigated with the simultaneous presentation of 4 AM²/FM tones associated with the aforementioned unique modulation frequency per ear. This approach was applied during the examination of unilateral CHLs, and the contralateral ear was masked using white noise set at 30 dB below the stimulus intensity (never exceeding 50 dB HL).

3. Dichotic single: both ears were stimulated with 1 carrier frequency modulated at 67 Hz for the left ear and at 69 Hz for the right ear only when no ASSRs up to 70 dB HL were recorded with the dichotic multiple approach. Owing to default restrictions, the MASTER system reverts to single stimuli per ear when intensities are higher than 80 dB HL. This stimulus condition was used for 4, 2, 2, and 12 threshold assessments at 0.5, 1.0, 2.0, and 4.0 kHz, respectively.

**METHODS**

**TABLE 1**

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of Subjects</th>
<th>Mean Age (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH</td>
<td>40</td>
<td>22 years (18-32)</td>
</tr>
<tr>
<td>SNHL</td>
<td>17</td>
<td>47 years (19-60)</td>
</tr>
<tr>
<td>CHL</td>
<td>7</td>
<td>36 years (25-54)</td>
</tr>
</tbody>
</table>

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ASSR RECORDINGS

Surface electrodes were positioned on the Cz (noninverting), Oz (inverting), and Fpz (ground), with all electrode impedances of 3 kOhms or less. Recordings were conducted in a double-walled, sound-attenuated booth, with participants sleeping or relaxing quietly on a bed. The electroencephalographic activity was filtered using a bandpass of 30 to 300 Hz (12 dB/ octave) and amplified by a gain of 10,000. Data were collected and digitized with an analog-to-digital conversion rate of 1200 Hz, with a 16-bit precision. The data were recorded in epochs containing 1024 points, and 1-response epoch lasted 0.853 seconds (1024 points/1200 Hz). Sixteen data epochs were collected and linked together to form 1 sweep with an overall duration of 13.653 seconds. An individual data epoch containing excessive myogenic noise was eliminated when amplitudes exceeded an artifact rejection level of ±40 µV. The next acceptable epoch was then used to construct the sweep, and online weighted averaging of the data was used to combine sweeps. Response evaluations were based on F ratio statistics, which compared the amplitude at the modulation frequency with the mean amplitude of the background noise in 120 adjacent frequency bins (60 bins above and 60 bins below the modulation frequency). A response was considered to be “present” when the F ratio, evaluated against critical F values with 2 and 240 df, was significant at a level of P < .05. Consequently, a “no response” was regarded as a response that did not reach significance (P ≥ .05) after a maximum amount of sweeps (as described in the next subsection).

ASSR THRESHOLD EVALUATION

To determine ASSR thresholds with the dichotic multiple and monotic multiple approaches, starting intensities were set at 50 dB HL for the NH group and at 70 dB HL for the hearing-impaired group. Intensities were decreased in 10-dB steps down to 0 dB HL for the NH group or until all responses were absent for the hearing-impaired group. One exception to this standard protocol was made for 2 hearing-impaired subjects who had only 1 significant response per ear at 70 dB HL. In these cases, the intensity was increased in 10-dB steps to 80 dB HL. Estimations of ASSR threshold with the dichotic single condition commenced at 90 dB HL and then decreased in 10-dB steps until no responses were recognized. This dichotic single condition was applied in 6 of 11 cases with sloping hearing loss and in 4 of 23 cases with flat hearing loss when only 1 or 2 carrier frequencies did not reach significance using the dichotic multiple approach. Each time it was adopted after first establishing ASSR thresholds for the other carriers using the standard multiple-frequency protocol. Stimulus presentation levels did not go below 0 dB HL or exceed 90 dB HL.

The ASSR recordings at each stimulus intensity were stopped if any of the following 2 criteria were met. First, the recording was ceased when all 8, 4, or 2 responses reached significance for the dichotic multiple, monotic multiple, or dichotic single conditions, respectively, and significance could be maintained for 8 consecutive sweeps. Second, the recording was stopped after attaining a maximum number of sweeps, even if not all responses reached significance. A maximum of 48 sweeps (or 11 minutes) was selected for the dichotic multiple and monotic multiple conditions because this amount forms a compromise between test duration and ASSR threshold accuracy. For the dichotic single approach, a maximum of 32 sweeps (or 8 minutes) was used mainly to minimize the recording time.

The ASSR thresholds were defined as the lowest intensity at which a significant response was detected, and a nonsignificant response was found 10 dB below this level. A secondary

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Table 1. Classification of NH, SNHL, and CHL Based on Otoscopy, Pure-Tone Audiometry, 226-Hz Tympanometry (Jerger-Liden Classification), and Ipsilateral Acoustic Reflexes at 0.5, 1.0, and 2.0 kHz and Etiology

<table>
<thead>
<tr>
<th>Measure</th>
<th>NH (n=40)</th>
<th>SNHL (n=17)</th>
<th>CHL (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Otoscopy</td>
<td>Normal findings</td>
<td>Normal findings</td>
<td>Retracted eardrum, Perforated eardrum, Intact neotympanum, Dry infection-free mastoid cavity</td>
</tr>
<tr>
<td>Pure-tone audiometry</td>
<td>AC ≤ 20 dB HL</td>
<td>BC ≤ 20 dB HL</td>
<td>ABG ≤ 10 dB HL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exceeded an artifact rejection level of ±40 µV. The next acceptable epoch was then used to construct the sweep, and online weighted averaging of the data was used to combine sweeps.</td>
</tr>
<tr>
<td></td>
<td>AC &gt; 20 dB HL</td>
<td>BC &gt; 10 dB HL</td>
<td>ABG &gt; 10 dB HL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Except for some sloping losses, AC thresholds at 0.25 kHz (10 ears), 0.5 kHz (2 ears), and 1.0 kHz (1 ear) were within normal limits.</td>
</tr>
<tr>
<td>Tympanometry</td>
<td>Type A</td>
<td>Type A</td>
<td>Type B</td>
</tr>
<tr>
<td></td>
<td>Normal threshold</td>
<td>Normal threshold (n=53)</td>
<td>Elevated threshold (n=31)</td>
</tr>
<tr>
<td>Acoustic reflexes*</td>
<td>Normal</td>
<td>Elevated</td>
<td>Absent</td>
</tr>
<tr>
<td>Etiology</td>
<td>Congenital idiopathic (7 adults)</td>
<td>GJB2 mutation 35delG (1 adult)</td>
<td>Drug induced (2 adults)</td>
</tr>
<tr>
<td></td>
<td>Chronic otitis media:</td>
<td>With cholesteatoma (4 adults):</td>
<td>(1) After canal wall-up surgery (2 adults);</td>
</tr>
<tr>
<td></td>
<td>Without cholesteatoma (3 adults)</td>
<td>Without cholesteatoma (3 adults)</td>
<td>Without cholesteatoma (3 adults)</td>
</tr>
</tbody>
</table>

*Acoustic reflexes: normal thresholds, 70 to 95 dB HL; elevated thresholds, 100 to 110 dB HL; absent reflexes, higher than 110 dB HL. For SNHL, the total number of acoustic reflex measurements is 102 (17 adults × 2 ears × 3 acoustic reflexes).
criterion was established to decide whether the lowest significant response was the real ASSR threshold when false-positive and false-negative results occurred. This rule stated that if the difference between a nonsignificant (higher intensity) and a significant response (lower intensity) was 20 dB or greater, the first significant response at a higher intensity level was determined to be the threshold (adopted 2 times of the 488 threshold assessments). If the difference was 10 dB, then the significant response at the lower intensity was decided to be the threshold (19 times of the 488 assessments).

DATA ANALYSES

The accuracy of the MASTER system in predicting behavioral thresholds was evaluated for various degrees, types, and configurations of hearing impairment. The measure of interest was the difference threshold, which was calculated for each carrier frequency by subtracting the behavioral from the ASSR threshold. All statistical analyses were performed with STATISTICA, release 7 (Statsoft Inc, Tulsa, Oklahoma). First, to assess the effect of degree of hearing loss, threshold results were classified into 4 categories based on the subjects’ pure-tone behavioral thresholds with each frequency considered separately. The categories were defined as follows: NH (0-20 dB HL), mild hearing loss (21-40 dB HL), moderate hearing loss (41-70 dB HL), and severe hearing impairment (71-90 dB HL). Second, the impact of abnormal middle ear function was assessed for 8 ears with CHL and compared with ears with SNHL (n=34) and NH (n=80). Third, the effect of audiometric configuration was examined because ears with SNHL could be divided into 2 groups: (1) the flat SNHL group had behavioral thresholds from 0.5 to 4.0 kHz that did not vary more than 20 dB across frequencies (n=23) and (2) the sloping SNHL group had behavioral thresholds occurring at equal or successively higher levels from 0.5 to 4.0 kHz and the difference between thresholds at 0.5 and 4.0 kHz was always greater than 20 dB (n=11). Finally, the effectiveness of the multiple-frequency 80-Hz ASSR diagnostic test was evaluated by comparing the ASSR thresholds to the criterion standard pure-tone threshold results. These behavioral thresholds were classified as “normal” or “hearing impaired” based on a criterion level of 20 dB HL or lower for normality. Accordingly, ASSR thresholds were also categorized as “normal” or “hearing impaired”; however, this time various cutoff criterion levels (≤20 dB HL, ≤30 dB HL, or ≤40 dB HL) were used to define normality. Subsequently, the effect of altering the ASSR cutoff criterion was examined for sensitivity, specificity, positive and negative predictive values, and efficiency.

RESULTS

DEGREE OF HEARING LOSS

The NH group and mild and moderate SNHL groups were considered for this analysis. Because of the low number of data (n=4), thresholds categorized as “severe hearing impairment” were excluded. Table 2 summarizes the mean behavioral, ASSR, and difference thresholds. A 2-way analysis of variance (ANOVA) (degree of hearing loss × carrier frequency) of difference thresholds revealed statistically significant main effects for degree (F1,440=4.01; P=.02) and carrier frequency (F3,440=3.07; P=.03). A post hoc analysis of the effect degree with the Tukey honestly significant differences test indicated that the mean difference levels of the moderate SNHL were significantly lower than those of the NH group, but the mild SNHL did not differ significantly from the moderate SNHL and normal thresholds. Post hoc comparisons of the effect carrier frequency demonstrated that the mean difference threshold at 0.5 kHz was significantly higher than at 1.0, 2.0, and 4.0 kHz and also that the mean difference threshold at 2.0 kHz was significantly lower than at 1.0 kHz. The interaction between degree of hearing loss and carrier frequency did not reach statistical significance.

Subsequently, the distribution of absolute ASSR thresholds were calculated for the NH and mild and moderate SNHL category at each carrier frequency and for all carrier frequencies combined (Figure 1). Overall results indicated that ASSR thresholds extended from 0 to 50 dB HL for the NH group, with a majority at 20 dB HL (42%); from 30 to 60 dB HL for the mild SNHL category, with a majority at 50 dB HL (50%); and from 40 to 90 dB HL for the moderate SNHL group, with a majority at 60 dB HL.

Table 2. Mean and Standard Deviation of Behavioral, ASSR, and Difference Thresholds by Frequency for Normal Hearing and Mild and Moderate Degrees of SNHL

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Normal Hearing</th>
<th>Mild SNHL</th>
<th>Moderate SNHL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD) No.</td>
<td>Mean (SD) No.</td>
<td>Mean (SD) No.</td>
</tr>
<tr>
<td>0.5 kHz</td>
<td>Behavioral, dB HL</td>
<td>ASSR, dB HL</td>
<td>Difference, dB</td>
</tr>
<tr>
<td></td>
<td>5 (5)</td>
<td>19 (10)</td>
<td>14 (7)</td>
</tr>
<tr>
<td>1.0 kHz</td>
<td>3 (4)</td>
<td>15 (8)</td>
<td>10 (8)</td>
</tr>
<tr>
<td>2.0 kHz</td>
<td>2 (5)</td>
<td>10 (8)</td>
<td>13 (8)</td>
</tr>
<tr>
<td>4.0 kHz</td>
<td>3 (6)</td>
<td>16 (9)</td>
<td>13 (8)</td>
</tr>
</tbody>
</table>

Abbreviations: ASSR, auditory steady-state response; SNHL, sensorineural hearing loss.

a No. refers to the number of thresholds defined according to degree of hearing loss based on the subjects’ pure-tone behavioral thresholds.
HL (40%). In addition, these overlapping results demonstrated that distinct separation can be made between NH and moderate SNHL, but differentiating mild SNHL from NH and mild from moderate SNHL is difficult. In particular, the “mild SNHL and NH” differentiation can be made best at 2.0 and 4.0 kHz (it should be noted that 4.0 kHz only had 4 thresholds categorized as mild), then at 1.0 kHz, and the worst distinction is at 0.5 kHz. For the “mild SNHL and moderate SNHL” differentiation, the opposite is true, and the order of best to worst differentiation would be made best at 0.5, 1.0, 4.0, and 2.0 kHz.

Finally, the relationship between ASSR and behavioral thresholds were assessed by calculating the Pearson product-moment correlation. As shown in Figure 2, all correlations demonstrated strong and statistically significant ($P < .05$) relationships with Pearson $r$ values of 0.82, 0.91, 0.94, and 0.94 for 0.5, 1.0, 2.0, and 4.0 kHz, respectively.

**TYPE OF HEARING LOSS**

Table 3 gives the mean behavioral, ASSR, and difference thresholds for ears with NH (n=80), SNHL (n=34), and CHL (n=8). A 2-way ANOVA (type of hearing loss × carrier frequency) of difference thresholds showed a main effect of type of hearing loss ($F_{3,470}=3.65, P = .03$) with the SNHL group demonstrating lower difference scores than the NH group. However, no statistical difference could be determined for the CHL group compared with the NH and SNHL group. Furthermore, a significant effect of carrier frequency ($F_{3,470}=2.64; P = .048$) was present with a higher difference level at 0.5 kHz than at all other carrier frequencies. No significant interaction could be observed between type of hearing loss and carrier frequency.

The relationship between behavioral and ASSR thresholds were assessed only for the ears with CHL (n=8) using the Pearson product-moment correlation. All correlation analyses were significant ($P < .05$), and the coefficients were 0.76, 0.89, 0.81, and 0.82 for 0.5, 1.0, 2.0, and 4.0 kHz, respectively.

**Figure 3**A illustrates air- and bone-conduction behavioral and air-conduction ASSR thresholds of a patient with chronic otitis media of the left ear without cholesteatoma and with an intact tympanic membrane, who underwent ASSR testing on 2 separate occasions. At the first test moment, the subject exhibited CHL, especially for the low frequencies. During a second occasion, a temporary deterioration of the middle ear status occurred, leading to elevated air-conduction behavioral thresholds across all frequencies. Apparently, the air-conduction ASSR thresholds accurately predicted the degree and configuration of the CHL at both test occasions.

**CONFIGURATION OF HEARING LOSS**

The mean behavioral and ASSR thresholds are plotted in Figure 3B for ears with flat (n=23) and sloping (n=11)
Figure 2. Pearson product-moment correlations between auditory steady-state response (ASSR) and behavioral thresholds at 0.5 kHz (A), 1.0 kHz (B), 2.0 kHz (C), and 4.0 kHz (D). HL indicates hearing level.

Table 3. Mean and Standard Deviation of Behavioral, ASSR, and Difference Thresholds by Frequency for Normal Hearing, SNHL (Sloping and Flat), and CHL

<table>
<thead>
<tr>
<th></th>
<th>0.5 kHz</th>
<th>1.0 kHz</th>
<th>2.0 kHz</th>
<th>4.0 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal hearing (n=80)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Behavioral, dB HL</td>
<td>4 (5)</td>
<td>3 (4)</td>
<td>2 (5)</td>
<td>3 (6)</td>
</tr>
<tr>
<td>ASSR, dB HL</td>
<td>24 (9)</td>
<td>18 (8)</td>
<td>12 (8)</td>
<td>16 (9)</td>
</tr>
<tr>
<td>Difference, dB</td>
<td>19 (10)</td>
<td>15 (8)</td>
<td>10 (8)</td>
<td>13 (8)</td>
</tr>
<tr>
<td>Combined SNHL (n=34)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Behavioral, dB HL</td>
<td>38 (14)</td>
<td>42 (14)</td>
<td>47 (12)</td>
<td>55 (11)</td>
</tr>
<tr>
<td>ASSR, dB HL</td>
<td>52 (16)</td>
<td>54 (14)</td>
<td>58 (11)</td>
<td>65 (12)</td>
</tr>
<tr>
<td>Difference, dB</td>
<td>14 (10)</td>
<td>12 (9)</td>
<td>11 (7)</td>
<td>10 (8)</td>
</tr>
<tr>
<td>Sloping SNHL (n=11)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Behavioral, dB HL</td>
<td>26 (6)</td>
<td>32 (8)</td>
<td>44 (17)</td>
<td>65 (10)</td>
</tr>
<tr>
<td>ASSR, dB HL</td>
<td>45 (11)</td>
<td>47 (14)</td>
<td>59 (14)</td>
<td>74 (10)</td>
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<tr>
<td>Difference, dB</td>
<td>19 (10)</td>
<td>15 (9)</td>
<td>15 (6)</td>
<td>9 (7)</td>
</tr>
<tr>
<td>Flat SNHL (n=23)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Behavioral, dB HL</td>
<td>44 (13)</td>
<td>47 (14)</td>
<td>49 (9)</td>
<td>50 (8)</td>
</tr>
<tr>
<td>ASSR, dB HL</td>
<td>56 (16)</td>
<td>57 (13)</td>
<td>57 (11)</td>
<td>61 (11)</td>
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<td>Difference, dB</td>
<td>12 (9)</td>
<td>10 (8)</td>
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<td>11 (9)</td>
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<tr>
<td>CHL (n=8)</td>
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<td></td>
</tr>
<tr>
<td>Behavioral, dB HL</td>
<td>41 (13)</td>
<td>37 (10)</td>
<td>30 (16)</td>
<td>38 (13)</td>
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<tr>
<td>ASSR, dB HL</td>
<td>55 (18)</td>
<td>49 (15)</td>
<td>46 (14)</td>
<td>49 (12)</td>
</tr>
<tr>
<td>Difference, dB</td>
<td>14 (12)</td>
<td>12 (8)</td>
<td>16 (9)</td>
<td>11 (8)</td>
</tr>
</tbody>
</table>

Abbreviations: ASSR, auditory steady-state response; CHL, conductive hearing loss; n, number of ears; SNHL, sensorineural hearing loss.
configurations of SNHL. Overall, the 80-Hz ASSR technique provided good threshold estimates for both audiometric configurations. Furthermore, Table 3 summarizes the mean behavioral, ASSR, and difference thresholds for these flat and sloping configurations. A 2-way ANOVA (configuration × carrier frequency) of the difference scores revealed only a significant main effect for configuration ($F_{1,128} = 8.75; P = \text{.004}$), with higher difference thresholds for the sloping SNHL than for the flat SNHL, except at 4.0 kHz where the differences were about equal.

The distributions of difference thresholds for both sloping and flat SNHL are presented in Figure 4. The ASSR thresholds were within 15 dB of the behavioral threshold in 86% of the flat and in 66% of the sloping configurations. In the flat SNHL group, 5 of the 92 ASSR threshold predictions underestimated behavioral thresholds by 5 dB at frequencies of 1.0 kHz (n=2), 2.0 kHz (n=1), and 4.0 kHz (n=2). A 10-dB underestimation occurred once at 0.5 kHz. In the sloping SNHL group, of the 44 ASSR threshold determinations at 4.0 kHz, only 1 underestimated the actual behavioral threshold by 5 dB. Further analysis demonstrated that this occurred in 1 of the 4 ears with steep-sloping losses ($\geq 30$ dB/octave), in particular for the most steeply sloping loss (45-dB drop between 2.0 and 4.0 kHz).

THE EFFECTIVENESS OF THE MULTIPLE-FREQUENCY 80-Hz ASSR TECHNIQUE

The effectiveness of the multiple-frequency 80-Hz ASSR diagnostic instrument was assessed for the NH and SNHL groups. Table 4 presents the sensitivity, specificity, predictive values and efficiency for each carrier frequency and all carrier frequencies combined. These values are inherently affected by the choice of the ASSR cutoff criterion ($\geq 20$, $\geq 30$, or $\geq 40$ dB HL) and prevalence (29% hearing loss based on behavioral audiometry). In general, sensitivity and negative predictive value deteriorates and specificity and positive predictive value improves as the ASSR criterion increases. With an ASSR
The obtained difference thresholds in Table 2 for the subjects with NH (10-19 dB) were similar to other comparable studies, and a higher difference score for the 0.5-kHz carrier frequency could also be demonstrated.7,13,21,22 The moderate SNHL difference scores were on average between 9 and 14 dB, showing once more a 0.5-kHz discrepancy (as discussed in the following paragraphs). These results were comparable with those of Lins and colleagues22 (9-13 dB) and higher than those of Swanepoel and Erasmus10 (2-8 dB). The latter finding can be attributed to the 10-dB-down and 5-dB-up ASSR threshold-seeking procedure as opposed to the descending search protocol with a 10-dB step size used in the present study. Furthermore, the mean difference threshold results for the mild SNHL were equal across frequencies (13 or 14 dB), but to our knowledge, no published data exist for comparison. Finally, only the moderate SNHL difference thresholds were significantly lower than the NH results, which is in agreement with the general consensus that the difference between ASSR and behavioral thresholds decreases as the severity of hearing loss increases.7,9,13,14,22 This phenomenon has been related to recruitment as a result of which the physiological response increases in amplitude more steeply with increasing intensity when patients have SNHL, making it easier to recognize the response at near-threshold intensities.7,14,22

Furthermore, the present research focused on investigating patients with mild SNHL (Table 2) because no 80-Hz ASSR study explicitly reported results for mild SNHL. In addition, the capability of the multiple-frequency 80-Hz ASSR technique to distinguish between normal, mild, and moderate degrees of SNHL was explored. As illustrated in Figure 1 by the amount of overlap between the absolute ASSR thresholds of the 3 categories, NH can be clearly distinguished from moderate SNHL, since no overlap exists for each carrier frequency and pooled frequencies. Furthermore, the “mild SNHL–NH” differentiation is particularly difficult for the 0.5 kHz carrier frequency and the “mild SNHL–moderate SNHL” separation is difficult for the 2.0 kHz carrier frequency. This 0.5-kHz discrepancy has already been extensively reported in previous research,7,13,22 and several factors might contribute to this phenomenon. The most likely explanation is related to issues of neural synchrony. There is probably greater latency jitter in the neurons responding to the low-frequency stimuli caused by both the broader activation pattern of the 0.5-kHz stimulus on the basilar membrane and the increased travel time to the apical region of the cochlea, where the traveling wave slows down. Consequently, this latency jitter decreases the size of the response at 0.5 kHz.7,22 Another possible reason may be that the stimulus protocols used to evoke the 0.5-kHz ASSR are not yet optimal. Use of lower modu-
lation (40-Hz) frequencies, AM² tones, or other optimized stimuli may yield better results.²⁰,²³,²⁴ Another potential explanation could be the enhanced masking effect of ambient acoustic noise at the lower frequencies.²²

In infants, differentiating mild SNHL from NH will probably be very difficult during the first few weeks of life because the 80-Hz ASSR technique seems to undergo notable developmental changes.²⁰,²⁵ Therefore, in the neonatal period, slightly elevated ASSR thresholds should be interpreted cautiously and cross-checked with the tone-burst ABR technique. Indeed, recent research has demonstrated that the tone-burst ABR technique offers a more reliable prediction of behavioral thresholds than the ASSR approach because the response is less susceptible to maturational processes during the first weeks of life.²³ Furthermore, the application of a 5-dB step size may be needed to improve ASSR threshold accuracy, although this will be a time-consuming process of threshold estimation.

**TYPES OF HEARING IMPAIRMENT**

To initiate appropriate medical and audiological intervention strategies, it is important to differentiate CHL from SNHL. The present study focused on evaluating subjects with CHL because relatively few studies have explicitly presented ASSR data for patients with actual CHL.⁷,¹⁰,¹¹ To our knowledge, only the research of Dimitrijevic and colleagues reported difference thresholds for simulated CHL and will serve for comparison. First, the difference between the air-conduction ASSR and behavioral thresholds for the CHL group did not significantly differ from the NH and SNHL group (Table 3), whereas in the study by Dimitrijevic et al.,⁷ the simulated CHL differences were significantly larger than the SNHL scores. This discrepancy may be attributed to the fact that the present sample was confined to mild and moderate SNHL, whereas their population sample consisted of subjects with mild to severe SNHL, a result of which the recruitment effect was more apparent with lower SNHL difference thresholds. Second, the present CHL results were lower than the simulated CHL difference scores. Lastly, by observing the 2.0-kHz frequency results (Table 3), the CHL difference threshold was higher than the difference score of the SNHL group and the simulated CHL group. This higher variability at 2.0 kHz for the CHL group might be related to the “Carhart-notch”—like phenomenon observed in several pure-tone audiograms, whereas the SNHL group consisted of flat and sloping configurations and the study by Dimitrijevic et al simulated a flat CHL. Furthermore, the audiograms in Figure 3A from the patient with chronic otitis media who experienced temporary deterioration of the middle ear status illustrated that the multiple-frequency 80-Hz ASSR method accurately reflects the degree and configuration of the air-conduction behavioral thresholds.

Despite these encouraging results, the type of hearing impairment cannot be identified as sensorineural, conductive, or mixed by assessing only the air-conduction ASSR thresholds. Therefore, bone-conduction ASSR testing should be incorporated to evaluate the degree of cochlear involvement. Although recent ASSR bone-conduction research with adults and infants with NH exhibited promising outcomes, normative bone-conduction ASSR thresh-

**CONFIGURATION OF HEARING LOSS**

The multiple-frequency 80-Hz ASSR technique accurately reflected the flat and sloping configurations of the behavioral audiograms as demonstrated by the mean audiometric results in Figure 3B and Table 3. Previous investigations with flat and sloping patterns also confirmed that multiple-frequency ASSRs can accurately predict behavioral audiometric configurations.¹²,²⁷ A direct comparison of the difference thresholds obtained in these studies and the present study is difficult because of some methodological variations such as differences in definition criteria of flat and sloping losses, threshold-seeking procedures and the intensity step sizes, AM vs AM/FM stimuli, and the averaging procedures. Nevertheless, some general trends can be observed. For the sloping SNHL group, the largest difference between ASSR and behavioral threshold was at the 0.5-kHz frequency and the smallest was at the 4.0-kHz frequency (Table 3). This finding could also be observed for the sloping difference thresholds in the studies by Herdman and Stapells¹² and Vander Werff and Brown²⁷ and is in agreement with the general belief that the accuracy of ASSR threshold estimations increases as carrier frequencies increase.²⁷ However, this carrier frequency effect was not apparent for the flat SNHL group, which had similar mean difference scores across frequencies (ranging from 9–12 dB). The research by both Herdman and Stapells¹² and Vander Werff and Brown²⁷ also demonstrated equal difference scores for the 1.0–, 2.0–, and 4.0-kHz frequencies but not for 0.5 kHz. This 0.5-kHz discrepancy might be attributed to the effect of degree (as discussed in the “Degree of Hearing Loss” subsection of this section) in the study by Herdman and Stapells,¹² since the mean behavioral threshold for the flat hearing loss was lower (32 dB HL) compared with the present study (44 dB HL), whereas for the Vander Werff and Brown²⁷ research, differences in averaging procedures can probably account for this discrepancy. Their averaging procedures consisted of 3 separate trials of 16 sweeps averaged together off-line to form 48 sweeps, whereas the present study averaged 48 sweeps online. Possibly, these 3 separate trials of 16 sweeps decreases the residual noise insufficiently when evoking responses at 0.5 kHz at near-thresholds intensities.¹⁴ As illustrated by these equal difference thresholds for the flat SNHL group, this carrier frequency effect shown in the published literature is probably related to the dominance of sloping high-frequency hearing loss in the hearing-impaired population.¹⁵

Finally, the frequency specificity of the multiple-frequency 80-Hz ASSR technique was considered by evaluating the sloping SNHL group. Especially, assessing ASSR underestimations of behavioral thresholds in subjects with very steep sloping losses (≥30 dB/octave) is interesting, to observe if any spread of activation exists along the basilar membrane toward better regions of the cochlea. Only 1 ASSR threshold prediction underestimated the behavioral threshold that occurred at 4.0 kHz for the most
THE EFFECTIVENESS OF THE MULTIPLE-FREQUENCY ASSR TECHNIQUE

The present study investigated the effectiveness of the multiple-frequency 80-Hz ASSR diagnostic test for several ASSR cutoff points by evaluating its sensitivity, specificity, predictive values, and efficiency. As given in Table 4, the 20-dB-or-lower ASSR cutoff criterion yielded a 100% sensitivity, meaning that all individuals with a hearing loss were detected by the ASSR technique. However, application of such a low criterion level resulted in an overall false-positive outcome of 20% for subjects who actually did not have hearing loss. Particularly, for the ASSR thresholds at 0.5 kHz, 49% were classified as hearing impaired when actually NH was present. Alternatively, using a 40-dB-or-lower cutoff criterion increased specificity to approximately 100%, resulting in identifying most persons with NH but at the cost of missing some patients who actually have hearing loss. This false-negative outcome is arguably the most serious type of audiological misdiagnosis because patients with a true permanent hearing loss would be deprived from medical and audiological intervention strategies. Therefore, the most appropriate ASSR cutoff point to differentiate adults with NH from hearing loss seems to be the 30-dB-or-lower criterion. As ASSR thresholds are approximately 10 to 15 dB higher in infants compared with adults, this 30-dB-or-lower criterion for adults is in agreement with normal ASSR screening levels of 40 to 50 dB HL for infants. Recently, Savio and colleagues examined the usefulness of a multiple-frequency 80-Hz ASSR technique (0.5 and 2.0 kHz) within the hearing screening context, and a 40-dB HL screening criterion resulted in 100% sensitivity and 95% specificity. Accordingly, the multiple-frequency 80-Hz ASSR application might have potential value as a frequency-specific screening technique, but further development is required.

CONCLUSIONS

The present study investigated the ability of the air-conduction multiple-frequency 80-Hz ASSR approach to determine the degree, and configuration of hearing loss. In adults, mild hearing loss can be distinguished from NH but difficulties may arise at the 0.5-kHz frequency, whereas for the “mild SNHL and moderate SNHL” differentiation, complications may occur at 2.0 kHz. Although air-conduction ASSR thresholds accurately estimated behavioral thresholds in patients with actual CHL, the type of hearing impairment cannot be determined by evaluating only these air-conduction ASSR thresholds, and bone-conduction ASSR measurements should be performed to establish the degree of cochlear involvement. Furthermore, there is a reasonable good cochlear frequency specificity, as indicated by assessing the sloping SNHL. Finally, when estimating ASSR thresholds using a descending search protocol with a 10-dB step size, a 30-dB-or-lower ASSR cutoff criterion for normality can be used in adults.

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