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Original Article

Prediction of aided and unaided audiograms using sound-field auditory steady-state evoked responses

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Abstract

Objective: To assess sound field auditory thresholds of hearing-impaired adults by using auditory steady-state evoked responses (ASSRs). *Design:* ASSRs were recorded to carrier frequencies of 500, 1000, 2000, and 4000 Hz, each uniquely modulated at a single frequency of 80–100 Hz. ASSR thresholds were compared to behavioral auditory thresholds. *Study sample:* Twenty adults (11 male, age 35.6 years) with moderate-severe sensorineural hearing loss who had used hearing aids, and 10 normal-hearing subjects (mean age 22.4 years). *Results:* For most frequencies, behavioral sound-field thresholds were slightly lower than ASSR thresholds in both aided and unaided conditions, with a significant correlation between them. Differences between ASSR and behavioral thresholds ranged between 516 dB in the unaided and between 5–16 dB in the aided condition. The ASSR amplitude growth function to 2000 Hz was steeper in both the aided and unaided conditions than in the normal-hearing group. *Conclusions:* Sound-field ASSRs can predict behavioral auditory thresholds in both the unaided and aided condition, as well as behavioral functional gains. The ASSR growth function for 2000 Hz is suggested to reflect an underlying mechanism of intensity encoding common to abnormal loudness perception frequently reported in cases of cochlear hearing loss.

Key Words: Auditory steady state evoked response; hearing aids; amplitude growth function; sound field ASSR; objective fitting

Since the introduction of universal newborn hearing screening, the first audiological diagnosis in infants has routinely been made at about five weeks of life (Attias et al, 2006b; Harlor & Bower, 2009). The ultimate goal of screening is twofold: to differentiate newborns with impaired hearing from those with normal hearing, and to manage hearing loss as early as possible, including fitting the infant with an aid that properly compensates for the loss and verifying that the aid provides adequate benefit (Scollie & Seewald, 2001). Both the full auditory diagnosis and the hearing-aid-fitting procedure should not extend more than a few months after screening to avoid a long period of auditory deficiency. A delay in diagnosis or management, particularly of congenital or early-onset hearing loss, may result in lifelong deficits in speech and language acquisition, poor academic performance, personal-social maladjustments, and emotional difficulties (Yoshinaga-Itano, 2004).

Clinical hearing assessments define the auditory thresholds for a wide range of frequencies. This information assists clinicians in prescribing an aid with the proper acoustic parameters to amplify the speech spectrum at a comfortable level, while ensuring that other sounds do not exceed the dynamic range of the subject (Byrne et al, 2001). To compensate for the combined effect of the amplified gain and the resonance characteristics of the individual ear, the real- ear output data of the hearing aid is also tested for a wide range of frequencies. To verify the hearing-aid fit, functional gain is determined together with a subjective assessment that may include a verbal report from the subject (Stelmachowicz & Lewis, 1988).

However, these modes are limited or impossible to apply in infants and other non-cooperative individuals. Even when suprathreshold auditory levels are observed behaviorally in infants, the findings are not repeatable and so cannot be used to estimate the aided and unaided hearing thresholds (for example, functional gain). At present, conservative means are usually employed, with less gain and output than in adults who are able to provide reliable behavioral responses (Snik & Stollman, 1998). The optimal approach for fitting hearing aids and verification in infants has not yet been established, and there remains a great need for an objective tool which can help to predict the aided and unaided audiogram and which, when coupled with the electroacoustic measurements, can provide sufficient data for appropriate hearing aid prescription (Littman et al, 2002).

The auditory steady-state response (ASSR) technique may offer a good solution, as previously suggested (Picton et al, 1998) and

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Abbreviations

ABR	Auditory brain stem responses
AM	Amplitude modulation
ANOVA	Analysis of variance
ASSR	Auditory steady state responses
Cz	Central midline as per the International 10–20 system
EEG	Electroencephalography
FFT	Fast Fourier transform
FM	Frequency modulation
ISO	International Organization for Standardization
SF	Sound field
SLM	Sound level meter

various variables were identified to affect its accuracy of threshold estimation (For further details see Meta Analysis, Tlumak et al, 2007). First, the ASSR is particularly attractive because it objectifies the threshold estimation process, it does not require the active cooperation of the subject, and the threshold responses are determined through objective statistical tests. Second, ASSRs have been repeatedly found to accurately predict behavioral auditory thresholds during bone and air conduction to a wide range of frequencies in infants, small children, and adults with hearing loss (Lins et al, 1996; John & Picton, 2000; Dimitrijevic et al, 2001, 2002; John et al, 2001; Cone-Wesson et al, 2002; Attias et al, 2006a). As the presentation level of the ASSR may be as high as 120 dBHL, with a frequency range of 500–8000 Hz, it is applicable even for subjects with severe to profound hearing loss and candidates for cochlear implants (Rance et al, 1998; Attias et al, 2006a). Third, in the author's experience, the sort of stimulus paradigms commonly employed for ASSR testing by means of speakers provide acceptably low levels of distortion for purposes intended, as also evaluated in the presently reported study. Therefore, coupled with the findings for unaided sound-field audiograms, the functional gain of hearing aids can be computed. Adding the electroacoustic measurements and the real-ear insertion gain to the aided ASSR audiogram would further improve hearing-aid selection and evaluation. The fourth important feature of ASSRs is the significant reduction in test duration, when multiple modulating tones are presented to both ears simultaneously. Although the risk of upward spread of masking may affect high frequencies, for the purposes of this study, it is believed that such compromises do not substantially affect tests of the ASSR in the sound field of adult subjects. Picton et al (1998) found that the sound-field ASSR test predicted the auditory behavioral aided pure-tone audiograms in children, with an average deviation from the behavioral thresholds of 13–17 dBHL for carrier frequencies across 500–4000 Hz.

Objectively determining comfortable and uncomfortable levels is an important challenge in fitting hearing aids in very young children and hard-to test subjects. A possible approach is to obtain the growth function of the ASSR amplitude to increased levels of stimulation and attribute the findings to abnormality in loudness perception associated with cochlear hearing loss.

Thus, the aim of the present study, conducted in adults in both aided and unaided conditions, was to assess the application of the ASSR test as an additional objective tool for evaluating the performance of hearing aids.

Material and Methods

Patients

The study was approved by the local Helsinki committee. Informed consent was obtained from all participants.

The study group consisted of 20 subjects, 9 female and 11 male, aged 24 to 60 years (mean 35.6 years) with different degrees of bilateral sensorineural hearing loss who had used digital hearing aids for at least five years. Table 1 lists the insert-phone behavioral audiogram values of the four tested frequencies (500, 1000, 2000, and 4000 Hz) in the hearing-impaired group. Eighteen subjects used bilateral hearing aids and two used a unilateral aid. The control group consisted of 10 subjects, aged 21–24 years (mean 22.4 years) with normal hearing. In the control group, audiometric thresholds for frequencies of 250–8000 Hz were equal to or less than 20 dBHL.

Behavioral auditory threshold test

All behavioral audiologic tests were carried out by skilled audiologists in a double-walled, sound-attenuated room (3.5 × 2.75 m) using calibrated audiometers (Interacoustic AC 40, Assens, Denmark). Pure-tone audiograms were obtained using an insert phone (Eartone 5A, Aearo Company, Indianapolis, USA) and sound-field (SF) speakers in the normal-hearing group and the hearing-impaired group in the unaided condition. SF audiograms were obtained in the aided condition. SF stimuli were presented simultaneously through two AC 40 interacoustic loudspeakers placed at an azimuth of 45° and a distance of 1.2 m from the subject's ears. All behavioral thresholds were performed using a 10-down/5-up dB paradigm following clinical convention/standards of 500, 1000, 2000, and 4000 Hz warble signals.

These stimuli resemble the ASSR amplitude-frequency-modulated tones and thus may be more appropriate for comparing hearing testing.

The outputs of the insert phone and loudspeakers were calibrated using a B&K Sound Level Meter (SLM) with a half-inch microphone (Skodsborgvej DK-2850; Naerum, Denmark). There was no more than a 1-dBSPL difference between the right and left insert phones, and all stimuli were within 1-dB of the levels set by the International Organization for Standardization (ISO) for etymotic insert phones (ISO 389-2, 1994). Level differences between the two speakers were equal to or less than 4 dBSPL for each of the four carrier frequencies tested.

ASSR recordings

ASSRs were assessed in a sound-attenuated room using the Bio-logic MASTER Version 2.02 (Bio-logic System Corp., Mundelein, USA). The potentials were collected from a scalp electrode located at Cz

Table 1. Insert-phone auditory behavioral thresholds for each ear in 20 subjects with sensorineural hearing loss.

Frequency (Hz)	*Right ear (dBHL)*	*Left ear (dBHL)*
500	42.7 ± 20.8	53.7 ± 22.8
1000	45.7 ± 19	49.7 ± 16
2000	48.3 ± 19.5	56.3 ± 18.5
4000	58.2 ± 19.5	62.2 ± 21.5

Note: Values are given as mean ± SD.

and referenced to the mid-line posterior neck (about 7 cm below the inion). The ground electrode was attached to the right mastoid. Electrode impedance was kept below 5 kOhm at 20 Hz. Subjects slept or drowsed in a reclining chair during testing.

ASSRs were collected at a sampling rate of 1200 Hz at 12-bit resolution. This rate prevents stimulus artifacts from interfering with the auditory modulation frequencies, thereby rectifying the aliasing effect. The electroencephalography (EEG) responses were amplified at a filter band-pass of 30–300 Hz. Consecutive data epochs of 1.024 seconds were linked together to form sweeps of 16.384 seconds, which were then averaged and analysed by fast Fourier transform (FFT) to yield an amplitude spectrum with a resolution of 0.061 Hz. Epochs that contained electrophysiologic activity exceeding 40 μV were rejected, and the next acceptable epoch was used to build the sweep.

To determine whether the FFT components at the stimulus modulation frequencies were different from the background EEG activity, the amplitude values at each of the carrier frequencies were compared by F ratio to the 120 adjacent frequencies (60 frequency bins above and 60 below the stimulus frequency, i.e. between -3.7 Hz and $+3.7$ Hz). The statistical significance was set at $p < 0.05$ (Picton et al, 2003). Frequencies at which other stimuli were modulated were excluded. The amplitude of the ASSR to a given carrier frequency was measured at the frequency of modulation for that carrier in the resulting amplitude spectrum.

Stimuli for the ASSR were sinusoidal tones that were 100% amplitude-modulated (AM) and 25% frequency-modulated (FM). Amplitude and frequency modulations were conducted at the same rate. A relative phase of 270° between the AM and FM components was chosen in order to elicit the largest combined response (John et al, 2001). The carrier frequencies were adjusted for maximum energy of the spectra at 500, 1000, 2000, and 4000 Hz for the left ear; the same carrier frequencies were then used for the right ear. The respective modulation rates were 82, 84, 86, and 89 Hz for the left ear and 91, 93, 96, and 98 Hz for the right ear.

In the normal-hearing group, ASSRs were recorded to insert-phone and SF auditory stimulation. During insert-phone testing, the auditory stimuli were presented by calibrated insert earphones with plastic tubes (Bio-logic System Corp.). The hearing-impaired group was tested by ASSR in SF mode only, with and without a hearing aid. Stimuli were calibrated at hearing level in the MASTER setup using the reference values of Wilber et al (1988). In the SF mode, the stimuli were delivered through the same speakers of the audiometer which were attached to a powerful amplifier (Max 250; Phonic America Corp., Tampa, USA) with a gain of 103 dB at 2000 to 5000 kHz. The SF auditory stimuli were calibrated by sound level measurements of the modulated tones at the four carrier frequencies tested, at the location of the subject's head in the sound-attenuated room, using the SLM system. When dissimilarities were noted between the stimulation level and the SLM measurements, the correction output table of the MASTER system was changed accordingly to match the target levels at each frequency. There were slight variations across the different carrier frequencies (up to 2 dB) and between the calibration sessions (up to 1 dB). The ASSRs were recorded for the right and left ear separately while the contralateral untested ear was masked by white noise using an insert phone and effective masking levels.

For auditory ASSR stimulation levels of less than 80 dBHL, multiple stimuli (four carriers with eight different modulation rates) were presented. For intensity levels of 80–132 dBHL, a single auditory presentation was used. This practice was intended to minimize the risk of multiple interactions among auditory stimuli presented simultaneously at levels above 80 dBHL and the risk of impairing hearing by high levels of auditory stimulation. In any case, if the stimulation caused discomfort to the subject, the recording was stopped immediately.

The ASSR threshold was defined as the lowest stimulus level at which there was a significant ASSR response. To determine the ASSR threshold, stimuli were presented at 20 dB above the behavioral insert-phone warble tone audiogram or the SF response. If the initial stimulus level failed to elicit a significant response, the intensity was increased by 20 dB until the response reached significance and completed the maximum 32 sweeps. Similar the behavioral paradigm, the ASSR threshold was performed by the 10-down/5-up dB method.

The absence of a response to any of the frequencies tested using the highest stimulus level was categorized as no response'. In cases of no response, the recording was stopped when the background noise reached 10 nV or after the maximum of 32 sweeps. The no response' events were excluded from the data analysis.

In the hearing-impaired group, ASSR thresholds were obtained for each of the test frequencies with and without the hearing aid. In the control group, ASSRs were recorded separately for insert-phone and SF stimulation.

To evaluate the ASSR amplitude growth as a function of stimulus intensity, each subject was presented with stimuli increasing from threshold to 20 and 40 dBSL in 10 dB steps for each of the four carrier frequencies (500, 1000, 2000, 4000 Hz), presented simultaneously. The growth function curve was computed by off-line analysis, separately for each frequency and for three levels: at threshold, and at 20 and 40 dB above threshold. After the ASSR threshold was computed, the ASSR amplitude to the subsequent stimulation levels was measured. The recording was stopped at the level at which the subjects signaled discomfort by pressing a button. Only those ASSR responses that were considered significantly different from noise floor were taken into account in growth function analysis.

To ensure that the frequency carrier stimulus for evoking the ASSR was not distorted by the hearing aid, real ear measurements were taken at the external ear canal with the AFFINITY Hearing Aid Analyzer System (Interacoustic; Essens, Denmark). The effect of ear canal resonance was measured in the unaided and aided conditions for 1000 and 4000 Hz carrier ASSR stimuli presented at 70 dBSPL via loudspeakers.

All ASSR and behavioral tests were conducted for each subject in one session, lasting approximately up to 2 hours for the hearing impaired group and 1 hour for the normal-hearing group.

Data analysis

SPSS for Windows (version 17; SPSS Inc., Chicago, USA) was used for all statistical analyses. The means, standard deviations, and differences between the behavioral and ASSR results in the SF unaided and aided conditions in the study group were computed for each tested frequency (500, 1000, 2000, and 4000 Hz) and over all frequencies. Analysis of variance (ANOVA) (behavioral/ ASSR thresholds × frequencies) was used to evaluate the differences between the behavioral and ASSR auditory thresholds across repeated measures (carrier frequencies). Differences in growth functions were analysed by comparing normal-hearing ($n = 20$ ears), aided and unaided conditions ($n = 38$ ears each) over three repeated measures (at threshold level, 20 dBSL, and 40 dBSL) using ANOVA, which takes into account the unequal number of ears between the control and study groups. Since in the current study, each ear was tested separately, the response of each was treated as an independent response and thus the repeated measures were over ears and Bonferroni correction was used in post-hoc analysis. The relationships between the ASSR and behavioral measures were assessed with Pearson's product moment correlations, and the variance was evaluated by squaring the coefficient correlation (r^2). Probabilities of less than 0.05 were considered significant.

Results

Figure 1 depicts the means and standard deviations of the unaided and aided SF behavioral and ASSR thresholds for each of the four frequencies and across all frequencies. The bottom panel of this figure presents the differences between the measures in the different conditions. Significant responses were recorded from all ears under all conditions, except in three ears in which no responses were obtained for 4000 Hz at maximum output of the ASSR system.

In the SF unaided condition, the mean threshold differences between the two measures across frequencies ranged from 5 to 16 dB. For most frequencies, the behavioral thresholds were lower (better) than the electrophysiological thresholds; only at 4000 Hz was the mean behavioral threshold higher. There was a significant correlation between the behavioral and electrophysiological thresholds in the hearing-impaired group, with coefficients of 0.94, 0.7, 0.64, and 0.6 at 500, 1000, 2000, and 4000 Hz, respectively. Squaring the coefficients (r^2) indicated that 88% to 36% of the variation can be explained by these correlations. Regardless of the carrier frequency, the correlation coefficient between the ASSR and behavioral thresholds was 0.82 ($F(1) = 0.07$; $p = 0.7$, NS).

In the SF aided condition, the mean behavioral threshold across all frequencies was lower by 6–10 dB than the mean ASSR threshold, with a significant difference between the two ($F(1) = 7.72$; $p < 0.009$). Contrast analysis showed that the behavioral thresholds were significantly lower than the ASSR thresholds at 2000 Hz ($p < 0.047$) and at 4000 Hz ($p < 0.002$). The correlations between the behavioral and ASSR thresholds were significant at 500 and 1000 Hz ($p < 0.001$), with coefficients of 0.84 and 0.82, respectively. Thus about 70% of the variation is explained by these coefficients. However, for the high frequencies of 2000 and 4000 Hz, the correlation coefficients were only 0.37 and 0.35, respectively, probably owing to the greater variance in the compression ratio of the hearing aids across frequencies.

The difference between the unaided and aided conditions was significantly larger for the behavioral thresholds than the ASSR thresholds; the average difference across all frequencies was 9 dB ($F(1) = 8.9$; $p < 0.006$). For the 4000 Hz carrier frequency, the difference in ASSR thresholds between the aided and unaided conditions was only 4 dB, whereas the difference in behavioral thresholds was 22 dB ($p < 0.0002$).

To rule-out substantial influence of distortion in the SF stimulus at the level of the ear canal during the ASSR test, real-ear measurements were used. Figure 2 shows the maximal (peak) output obtained at the frequency of the carrier stimuli (1000 or 4000 Hz) at 70 dBSPL in the aided and unaided conditions and the additional amplification due to the resonance of the ear canal. The resulting stimuli were used to evoke the ASSR responses. These findings indicate that there was no change in the maximal peak frequency as a consequence of the external ear canal effect or use of an aid, although low level harmonic distortions may exist.

To determine if the thresholds obtained using insert phones were comparable to SF stimulation, both modes were applied in the ASSR test of the normal- hearing group. The results are shown in Table 2. There was no significant difference in the ASSR thresholds between the two stimulation modes, indicating that the stimulation set-up was calibrated.

To evaluate the effect of stimulus intensity on ASSR amplitude, the ASSR growth function in response to an increase in stimulus

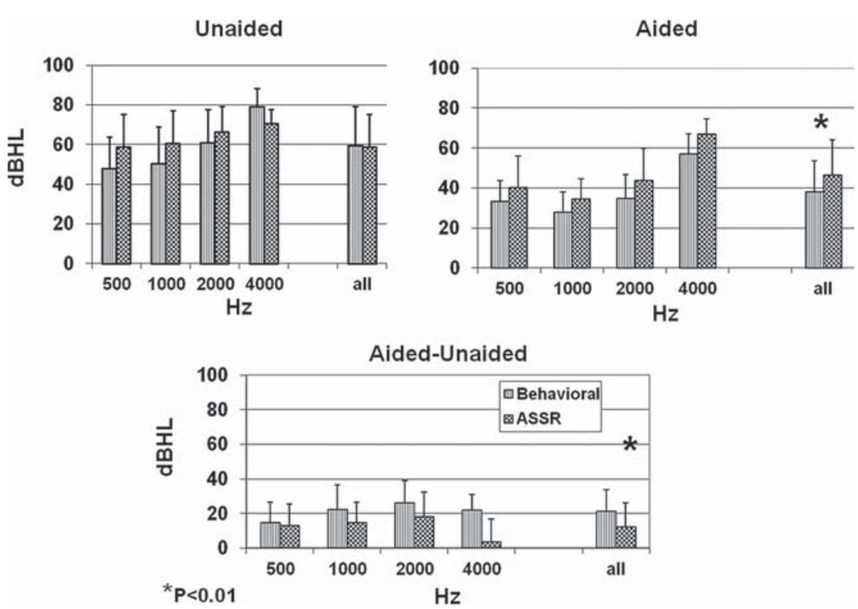

Figure 1. Means and standard deviations of SF behavioral and ASSR thresholds for each of four carrier frequencies and overall frequencies in the aided and unaided conditions. The bottom panel presents the gains computed by the behavioral and electrophysiological measures. Irrespective of frequency, the behavioral thresholds were significantly better than the ASSR thresholds in the aided condition, and the gains were significantly lower.

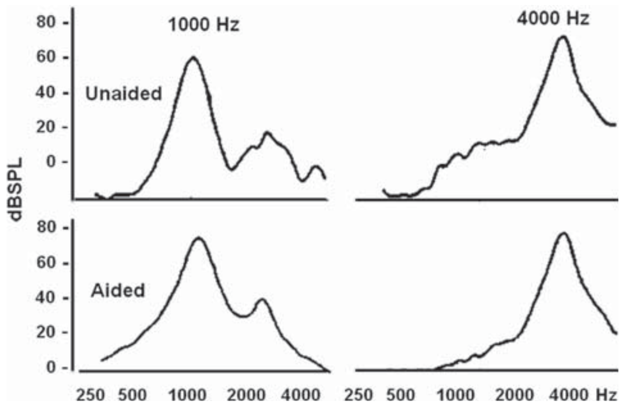

Figure 2. Real ear measurements for 1000 and 4000 Hz in the aided and unaided conditions. There was no change in the maximal peak frequency as a consequence of the external ear canal effect or use of an aid, although low level harmonic distortions may exist.

intensities above threshold for the mid-frequencies (1000 and 2000 Hz) was plotted for the normal and hearing-impaired group. It was impossible to calculate the growth function for 4000 Hz because of the small number of aided and unaided ears that exhibited a significant response at this frequency for suprathreshold levels (20 and 40 dBSL). The 500 Hz frequency was not analysed because of the large difference from behavioral thresholds and the risk of noise contamination. The means and standard deviations of the amplitudes are shown in Figure 3. All ASSRs were significantly above noise level. Thus, in the hearing-impaired group, owing to the severity of the hearing loss and the limited maximum output of the ASSR system, responses were obtained for the mid-frequencies for at least 73% of the ears at 20 dBSL and for at least 46% of the ears at 40 dBSL. All the normal-hearing subjects had responses at the threshold and at the two suprathreshold levels.

For the 2000 Hz carrier frequency, mean ASSR amplitude increased significantly in the hearing-impaired group with an increase in stimulus intensity. In the normal-hearing group, an increase was noted at 20 dBSL, without an additional increase between 20 and 40 dBSL. Two-way ANOVA (two groups (normal-hearing and hearing-impaired × 3 stimulus levels (at threshold level; 20 dBSL, and 40 dBSL)) with repeated measures indicated that the stimulus level had a significant effect on the ASSR amplitude ($F(2) = 76.8$; $p < 0.0001$). There was a significant interaction between group and ASSR growth function ($F(4) = 8.57$, $p < 0.001$). In the unaided condition, post hoc analysis revealed that the growth function was steeper than in the normal-hearing group, with significantly higher amplitudes at 20 and 40 dBSL ($p = 0.02$ and $p < 0.01$, respectively).

For the 1000 Hz carrier frequency, mean ASSR amplitude increased with an increase in stimulus intensity in both the normal-hearing group and the aided condition; in the unaided condition, higher sensation levels were associated with a decrease in ASSR amplitudes. ANOVA with repeated measures showed a significant impact of stimulus sensation level on ASSR amplitude over all groups ($F(2) = 41.4$, $p < 0.0001$); a significant interaction between groups and growth pattern ($F(4) = 5.1$, $p < 0.001$); and a significant difference between groups ($F(2) = 8.9$, $p < 0.001$). On post hoc analysis, the ASSR amplitude for 40 dBSL was lower in the unaided condition than in the aided condition and in the normal-hearing group.

Table 2. Insert-phone and SF ASSR thresholds in normal-hearing subjects.

	*ASSR threshold (dBHL)***		
Frequency (Hz)	*Insert phone*	*Sound field*	*Difference***
500	27.8 ± 8.3	37.8 ± 9.7	− 10.0
1000	26.7 ± 5.0	18.9 ± 9.6	7.8
2000	20.0 ± 5.0	17.8 ± 8.3	2.2
4000	22.2 ± 6.7	24.4 ± 12.3	− 2.2
Overall	24.1 ± 6.9	24.7 ± 12.1	0.6

Note: Values given as mean ± SD.
**All differences between insert-phone and SF thresholds were not statistically significant.

Discussion

The present study evaluated the relationship between SF ASSR and behavioral thresholds in adults with sensorineural hearing loss under aided and unaided conditions for frequencies of 500, 1000, 2000, and 4000 Hz. The difference in ASSR thresholds and amplitude growth function between the aided and unaided conditions was determined as well. The results showed that in the unaided condition, the SF pure-tone auditory thresholds for 500–2000 Hz could be predicted from the SF ASSR thresholds by the differences between the two measures and the correlations of the two means. In the unaided condition, the correlation coefficients ranged from 0.94 for 500 Hz to 0.64 for 2000 Hz and 0.6 for 4000 Hz, with corresponding r^2 ranged between 88% to 36%; the mean ASSR thresholds were higher by 16.3 to 5.3 dB across these frequencies. The better behavioral thresholds for the SF pure tones may be attributable to the contribution of attention and other cognitive functions associated with subjective hearing in audiometric tests, which are absent in ASSRs to high modulation rates (more than 60 Hz) (Jerger et al, 1986), and to the presence of EEG noise in the evoked potential recordings.

The results in the aided condition for the lower frequencies (500 and 1000 Hz) differed from those for 4000 Hz, which yielded a relatively low correlation coefficient ($r = 0.35$) and a high percent of unexplained variation (13%) between the ASSR and behavioral audiometric test, in addition to a better ASSR threshold for the low frequency range (by mean of 8.3 dB). This discrepancy may be explained by the pinna effect in the behavioral test despite the use of a warble tone. Although the loudspeakers were placed at an azimuth of 45° and a distance of 1.2 m from the ear, it was speculated that during the 4000 Hz warble tone in the SF tests, the subjects failed to consistently keep their ears in this azimuth, and the decreased amplification at the high frequencies due to the auricle and external ear canal led to a slightly attenuated threshold. The pinna effect is not observed during the ASSR test, in which the 4000 Hz stimulus is modulated at a low frequency (89 or 98 Hz). Previous studies demonstrated that a 3900 Hz tone can be lateralized on the basis of interaural time differences if it is modulated at a low frequency (300 Hz) (Henning, 1974). Others have also found that if a high-frequency tone is interrupted (modulated) periodically, the subject will perceive a pitch corresponding to the frequency of the modulation rate (McFadden & Pasanen, 1976). Of course this explanation must be confirmed in a controlled study.

The ASSR threshold for 4000 Hz may be also affected by the spread of the masking phenomenon, where low frequencies mask high frequencies during multiple-frequency stimulation at a high

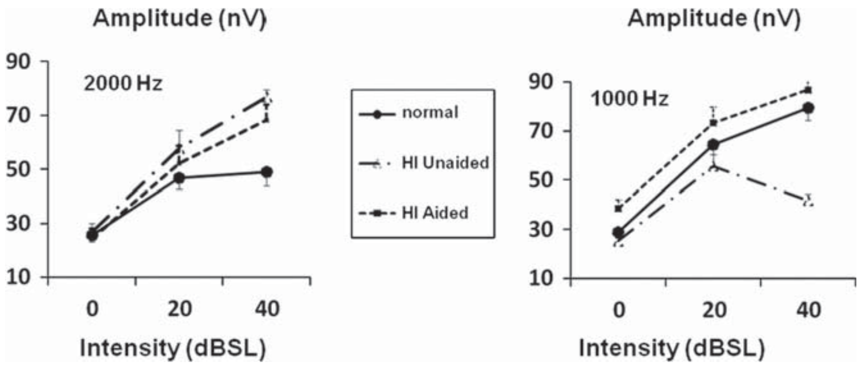

Figure 3. Means and standard deviations of the ASSR amplitude growth as a function of stimulus intensity for 1000 and 2000 Hz in the aided, unaided, and normal-hearing conditions. Growth function was significantly steeper at 2000 Hz in the unaided group compared to controls.

level. However, it was found that the mean values for the SF behavioral threshold and the ASSR threshold were similar over all frequencies and well correlated. Similar reports on validity and reliability of insert-phone ASSR in testing hearing threshold was found in previous studies using normal-hearing subjects subjected to a simulation of various degrees of hearing loss by filtered masking noise (Kaf et al, 2006a, 2006b).

In the SF aided condition, for each frequency and across all frequencies, the behavioral thresholds were significantly better than estimated by the ASSR, by a mean of 7 dB for 500 Hz to a maximum of 10 dB for 4000 Hz. In contrast to the unaided condition, the ASSR threshold was worse than the behavioral threshold for 4000 Hz. This may be explained by the absence of a pinna effect because the stimuli were picked up by the hearing-aid microphones placed above the auricle. Nevertheless, compared to the 500, 1000, and 2000 Hz frequencies for which correlations between the ASSR and behavioral thresholds were relatively high in both the aided and unaided conditions, for the 4000 Hz frequency, the correlation was low.

In the present study, the correlation coefficients between the ASSR and behavioral thresholds were higher for 500 Hz than for 1000 and 2000 Hz in both the aided and unaided conditions. Previous studies reported lower correlations for this frequency relative to higher frequencies (Lins et al, 1996; Attias et al, 2006a). This variability may be attributed to differences in the mode of stimulation (SF versus insert phone or earphone) and differences in the setting environment and subjects (hearing-impaired with and without hearing aids versus hearing-impaired unaided).

Thus, in both the aided and unaided conditions, the auditory behavioral thresholds for 500 and 1000 Hz could be reliably and objectively predicted by the ASSR thresholds. Improving the fixation of the head toward the loudspeakers and using a single-stimulus presentation may enhance the correlations between the ASSR and behavioral thresholds for 2000 and 4000 Hz as well.

For the ASSR test to serve as a feasible tool for evaluating aided and unaided thresholds, it is necessary that the hearing-aid amplification should not distort the modulation frequency of the stimuli. In the present study, the results of the real-ear measurements for 1000 and 4000 Hz modulated tones, presented at 70 dB and at the most comfortable level, revealed that in all conditions, the frequency of carrier stimulation was preserved, although low level harmonics may exist but did not affect the ASSR response at that frequency. This finding is important considering that hearing-aid selection is based mainly on the frequency gain characteristics of the aid for a given hearing loss. However, this study did not test the possible interactions between the various stimuli in terms of levels and frequencies, especially in the aided condition, and further research is required to elucidate this issue.

Besides predicting aided and unaided thresholds, to apply the ASSR test to proper selection of hearing aids, it is necessary to understand the ASSR growth function curve. Our preliminary evaluation of the relationship between ASSR amplitude and stimulus intensity showed that the pattern of growth functions differed among the normal condition and the aided and unaided hearing-loss conditions and between 1000 and 2000 Hz. For the 2000 Hz carrier frequency, the ASSR amplitude grew in the aided and unaided condition; however, growth in the unaided condition was significantly steeper than in the normal-hearing subjects, especially at the high sensation level. The finding of lower ASSR amplitudes in the normal-hearing than the hearing-impaired subjects is consistent with a previous study (Dimitrijevic et al, 2002). The steeper growth function in the unaided condition probably reflects the abnormality in loudness perception associated with cochlear hearing loss (Moore, 1989). When the same subjects were tested with hearing aids, the curve became less steep, probably owing to compression of the signals by the aid. The loudness abnormality in cochlear disorders is manifested primarily at high frequencies (2000 Hz and above) and has questionable relevance at lower frequencies (Yantis & Decker, 1964; Jerger, 1973). Indeed, the pattern of ASSR growth amplitude at 1000 Hz was substantially different from 2000 Hz. The reason for this pattern is unclear and may result from limited sample size and or/ other aspects of cohorts of subjects. In any case, a caution must be taken before interpretation of growth function and further studies are needed.

Auditory evoked potentials have been used in the past to assess the performance of hearing aids. In most reports, the hearing aid was adjusted until the latency of the wave V induced by click stimuli decreased to within normal range (Kileny, 1982; Hecox, 1983; Mahoney, 1985). This procedure is limited primarily because auditory brain responses (ABRs) to clicks are mainly related to high frequency gain, and because the correlation between wave V latency and loudness is low, particularly when there is a sloping hearing loss (Serpanos et al, 1997). Moreover, the very brief duration of the click subjects it to a risk of significant distortion, by electromagnetic artifacts for example, which may last up to 20 ms after onset when presented through hearing aids. The clicks may also be distorted by the loudspeakers, and the resultant artifacts can obscure the interpretation of the response (Kileny, 1982; Mahoney, 1985). Other investigators used the amplitude-intensity function of unaided click-evoked ABRs to predict the optimal gain for hearing aids (Kiessling, 1982; Davidson et al, 1990). This approach, too, is problematic because the ABR amplitude is loosely correlated with loudness. In general, hearing aids handle rapidly changing acoustic stimuli differently from more continuous stimuli such as speech, and it is difficult to predict the steady-state characteristics of hearing aids from ABR onset responses (Gorga et al, 1987).

Picton et al (1998) were the first to report on aided thresholds using ASSR in children (n = 35), followed by Stroebel et al (2007), who reported similar data in infants (n = 6). The present study complements and broadens the possible application of the ASSR in evaluating aided and unaided thresholds in adults. The differences between the physiological and behavioral thresholds in the aided condition ranged between 6 and 10 dB across 500, 1000, 2000, and 4000 Hz in the present study and between 13 and 17 dB in the study of Picton et al (1998). Similar differences between the behavioral and physiological measures were obtained in infants (Stroebel et al, 2007). The discrepancies from adults may be primarily due to the better accuracy of the behavioral threshold measurements in older patients.

For the 500, 1000, and 2000 Hz frequencies (excluding the 4000 Hz frequency for the reasons described above), the mean difference between the aided and unaided conditions in the ASSR threshold was similar to the mean difference in the behavioral threshold. Thus, the ASSR test may predict the improvement in the aided threshold, as reflected by the functional gain in the behavioral audiogram.

In conclusion, the present study supports the application of the ASSR test of hearing thresholds for the objective evaluation of the benefit of hearing aids in individual patients. The ASSR test may solve the problem of subjective testing in young or uncooperative patients. On the basis of our findings, further investigations of this promising tool are warranted.

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