Auditory steady-state response thresholds of adults with sensorineural hearing impairments

Abstract
This study evaluated the use of multiple auditory steady-state responses (ASSRs) to estimate the degree and configuration of behavioral audiograms of subjects with sensorineural hearing impairments. Place specificity of the multiple-ASSR method was also assessed. Multiple amplitude-modulated (77–105 Hz) tones (500, 1000, 2000 and 4000 Hz) were simultaneously presented to one ear. The results showed that, on average, multiple-ASSR thresholds were 14±13, 8±9, 10±10 and 3±10 dB above behavioral thresholds for 500, 1000, 2000 and 4000 Hz, respectively. Behavioral and multiple-ASSR thresholds were significantly correlated (r=0.75–0.89). There were no significant differences between behavioral and multiple-ASSR measures of the audiogram configuration. In subjects with steep-sloping ≥30 dB/octave hearing losses, multiple-ASSR thresholds did not underestimate behavioral thresholds, revealing good place specificity. These results indicate that the multiple-ASSR method provides good estimates of the degree and configuration of hearing in individuals with sensorineural hearing impairments.

Introduction
Several studies have found that auditory steady-state responses (ASSRs) to single amplitude-modulated (AM) tones accurately estimate hearing thresholds in individuals with sensorineural hearing impairments, with differences between behavioral and ASSR thresholds ranging from 4 to 8 dB (Aoyagi et al, 1993; Rance et al, 1995, 1995). (ASSRs are also commonly referred to as amplitude-modulated following responses or steady-state evoked potentials (SSEPs). A common nomenclature is needed for ease of discussion and clarity when considering evoked potentials in other sensory modalities. For instance, the acronym SSEP may be mistaken for somatosensory evoked potentials, and will lead to confusing dialogues between scientists and clinicians; a consensus is therefore needed. The term auditory steady-state responses, with the acronym ASSR, has been chosen for this paper.) Rance et al (1998) report correlations of 0.96–0.99 between ASSR and behavioral thresholds for AM/frequency-modulated (FM) tones between 500 and 4000 Hz. Aoyagi et al (1999) report a correlation of 0.88 for a 1000-Hz AM tone modulated at 80 Hz. These results indicate that the single-ASSR method can accurately estimate hearing loss. However, a key advantage of using ASSRs to evaluate hearing
thresholds is that ASSRs may be evoked by simultaneously presenting at least four separate AM tones per ear (Herdmann & Stapells, 2001; John et al., 1998; Lins et al., 1995, 1996).

A few studies have investigated the multiple-ASSR method’s ability to estimate hearing thresholds of subjects with hearing impairments. Picton and co-workers, in two separate studies, tested young children with hearing impairments (range 20–75 dB HL), and showed that multiple-ASSR thresholds are within 9–17 dB of behavioral thresholds (Lins et al., 1996; Picton et al., 1998). Correlations between behavioral and multiple-ASSR thresholds range from 0.54 to 0.91 for octave frequencies between 0.5 and 4.0 kHz (Lins et al., 1996; Picton et al., 1998). However, the results of these studies were obtained in high ambient noise environments, which elevated the absolute threshold estimations. Behavioral thresholds in the study by Lins et al. (1996) also show a restriction of range and clustering around the mean. Because there were only four subjects with hearing losses greater than 65 dB HL, and none with losses greater than 80 dB HL, it may be misleading to conclude that the multiple-ASSR method is useful for estimating hearing thresholds in patients with severe-to-profound hearing losses. Additionally, a postulated masking effect (Picton et al., 1998) of low-frequency (e.g. 500-Hz) AM tones masking ASSRs to high-frequency (e.g. 4000-Hz) AM tones when simultaneously presenting multiple stimuli may be greater for cases of severe-to-profound sensorineural hearing loss. Therefore, the moderate-to-good correlations between behavioral and multiple-ASSR thresholds may not be consistent for greater degrees of hearing impairments. Thus, it was an objective of the current study to replicate and extend previous results by obtaining, in a quiet environment, multiple- and single-ASSR thresholds from a sample of subjects with a wide range of hearing impairments (from 20 to 90 dB HL).

Another objective of the present study was to determine whether or not inclusion of low-frequency stimuli (e.g. 500 Hz) in the multiple-ASSR method would mask ASSRs to high-frequency AM tones (e.g. 4000 Hz). For example, if multiple-ASSR thresholds for 4000 Hz are significantly higher than those for the single-ASSR method, then it may be assumed that in the multiple-stimulus condition the lower-frequency stimuli are masking/altering the response to the 4-kHz stimulus (Picton et al., 1998). Picton and co-workers (Dimitrijevic et al., 2002; Picton et al., 1998) reported results from a few subjects with hearing impairments that showed that single ASSRs were better estimates of behavioral thresholds than were elevated multiple-ASSR thresholds. The current study further investigates this issue of masking, by obtaining results from a greater number of subjects.

To date, only one study has used statistical analysis to assess how well multiple-ASSR thresholds match the configuration of behavioral audiograms (Perez-Abalo et al., 2001). Therefore, further evaluation of this is being conducted in the present study, and will add to the limited data previously reported.

There is little information regarding multiple-ASSR threshold estimates in subjects with steep-sloping hearing losses. Subjects’ audiograms in the study by Perez-Abalo et al. (2001) have relatively flat configurations, and there is little information regarding the audiogram configurations in the studies by Picton and co-workers. The present study objectively evaluates the multiple-ASSR method for its threshold sensitivity and ability to match audiogram configurations of subjects with steep-sloping, as well as with flat/shallow-sloping, hearing impairments.

ASSRs to single and multiple AM tones (500–4000 Hz) have been shown to primarily reflect activation of approximately 1-octave-wide regions centered within ¼ octave of the carrier frequency, at least in subjects with normal hearing (Herdmann et al., 2002). If a subject has a steep-sloping hearing loss, adjacent cochlear regions that have lower thresholds may respond and cause an underestimation of the threshold at the frequency of interest. Underestimation of behavioral thresholds may occur when using brief-tone auditory brainstem responses (ABRs) (without notched-noise masking) to estimate hearing thresholds in individuals with steep-sloping hearing losses (Picton et al., 1979; Stapells et al., 1985, 1994). Therefore, it was an objective of the present study to determine if this occurs when multiple ASSRs are used to evaluate thresholds in such individuals.

The current study investigates the ASSR thresholds to single and multiple AM tones in order to determine the threshold sensitivity as well as the ability of multiple-ASSR method to match the configuration of the behavioral audiogram. Additionally, this paper investigates ASSR thresholds in individuals with steep-sloping hearing loss to evaluate the place specificity of the multiple-ASSR technique. Finally, ASSR thresholds are compared between single- and multiple-stimulus conditions to determine if there is any masking due to inclusion of lower-frequency AM tones.

Materials and methods

Subjects
Thirty-one adults (27 male) with sensorineural hearing impairments participated in this study. Their ages ranged from 25 to 94 years (mean = 63 years). Participants were selected based on their behavioral pure-tone audiograms in order to cover a wide range of hearing impairments across four frequencies (0.5, 1, 2 and 4 kHz). Twenty-six participants were tested in the sound-attenuated booth at the Workers’ Compensation Board of British Columbia. Sensorineural hearing impairments for these 26 individuals were confirmed by behavioral bone-conducted thresholds being within 10 dB of air-conducted thresholds. Behavioral (air and bone conduction) and ASSR thresholds were evaluated on the same day. Five other participants were tested in the sound-attenuated booth at the Human Auditory Physiology Laboratory (University of British Columbia). Air conduction thresholds for these five participants were obtained on the same day as ASSR testing; each subject had confirmed sensorineural hearing impairment by previous audiological assessment at other clinics. Acoustic immittance measures confirmed normal middle ear function for all participants on the day(s) of testing. A participant’s audiological results were obtained and used for analysis only after consent was obtained.

To allow a recording session to take a practical period of time, only one ear from each subject was tested. Selection of the test ear was based on three selection criteria. First, because of their infrequent occurrence, impairments sloping towards the low frequencies (i.e. ‘reverse’ slope) were chosen over losses sloping towards the high frequencies (n=1). Second, the ear which had a greater sloping impairment between octave frequencies was selected next (n=27). Third, the ear with a greater impairment was selected (n=3). Pure-tone behavioral thresholds

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for all subjects are presented in the Results section (see Figure 2).

**ASSR stimuli**

Stimulus and recording parameters were based on those previously reported by Lins et al. (1996) and Herdman & Stapells (2001).

Air-conducted stimuli were presented through Eartone 3A insert earphones. Stimuli consisted of sine waves at carrier frequencies of 500, 1000, 2000 and 4000 Hz that were 100% AM at frequencies of 77.148, 84.961, 92.773 and 100.586 Hz, respectively. To obtain the desired presentation level, AM stimuli were presented through a clinical audiometer. Stimulus intensities were calibrated in dB SPL for each carrier frequency (Quest Electronics model 1800 sound level meter; linear mode; Bruel & Kjaer DB0138 2-cc adapter) and adjusted to obtain dB normal hearing levels (nHL) from the audiometer. Adjusted 0 dB nHL values for AM tones of 500, 1000, 2000 and 4000 Hz were 11, 9.8 and 7 dB SPL, respectively (Herdman & Stapells, 2001).

Two stimulus conditions were used: (1) multiple—simultaneous presentation of four AM tones (500, 1000, 2000 and 4000 Hz); and (2) single—either 500-, 1000-, 2000- or 4000-Hz AM tones were presented separately, depending on the frequency of interest. To minimize recording time, one ‘frequency of interest’ for the single-stimulus condition was designated. This was the frequency within the steepest-sloping portion of the audiogram with the greatest behavioral threshold.

For the multiple-stimulus condition, all carrier frequencies were presented at the same intensity, and stimulus energy at frequencies with better hearing could result in temporary or permanent threshold shifts. To ensure that this would not happen, the following precautions were taken. First, intensity levels did not exceed 90 dB nHL, because the recording time needed to obtain a reasonable electroencephalographic (EEG) noise level (see below) would exceed safety limits if higher stimulus levels were assessed. Second, at 90 dB nHL, stimulation time was limited to three trials of 3 min, with two inter-trial, no-stimulus periods of 3 min (i.e. a 50% duty cycle).

**Procedure**

Behavioral and ASSR measures were obtained in one session lasting approximately 1.5 h at the Workers’ Compensation Board of British Columbia (n=26) or at the Human Auditory Physiology Laboratory on the campus of the University of British Columbia (n=5). Of the five subjects tested at the Human Auditory Physiology Laboratory, three subjects returned for an additional session of 2 h so that single-stimulus results could be obtained. During the behavioral measurements, participants relaxed in a comfortable reclining chair in a double-walled sound-attenuated booth. During ASSR measurements, participants slept or relaxed.

Background acoustic noise levels for 1-octave-wide bands centered at 0.5, 1, 2 and 4 kHz were 13, 9, 9 and 10 dB SPL, respectively, in the sound-attenuated booth at the Workers’ Compensation Board, and 12, 10, 10 and 12 dB SPL, respectively, in the sound-attenuated booth at the Human Auditory Physiology Laboratory.

Recording electrodes were placed at the vertex (Cz) and on the back of the neck, just below the hairline in the mid sagittal plane. A ground electrode was placed on the forehead. Inter-electrode impedances were less than 3 kOhm at 10 Hz. The EEG was amplified 80 000 times, and filtered using a bandpass of 30–250 Hz (12 dB/octave). An EEG recording sweep lasted for 16,384 s, and contained 16 sections of 1,024 s each. ASSRs were analyzed in the frequency domain by fast Fourier transform (FFT) of the average time-domain waveforms. The FFT resolution was 0.061 Hz, ranging from 0 to 250 Hz. In order to determine whether a response at the modulation frequency was different from the background EEG noise, an analysis of variance (i.e. the ‘F-technique’) (Dobie, 1993; Picton et al., 1987; Valdes et al., 1997; Zurek, 1992) was used to compare the FFT components at the modulation frequency with the 120 adjacent frequency bins (60 above and 60 below the modulation frequency, or ±3.7 Hz). A response was considered ‘present’ when the F-ratio of the signal to noise was significant if \( p < 0.05 \). A ‘no-response’ was accepted after the EEG background noise amplitude around the frequency of interest was less than 10 nV and \( p > 0.20 \). Approximately 2% (11/660) of response assessments missed the noise criteria for a ‘no-response’ by only 2 nV. A ‘no-response’ was still accepted for these recordings, because the p-values were greater than 0.50, indicating a low chance of obtaining a response with a few more averages, and the EEG noise level was reasonably low (i.e. ≤12 nV).

**Behavioral and ASSR threshold evaluation**

Behavioral thresholds were obtained using a Hughson-Westlake procedure (Carhart & Jerger, 1959) for pure tones at 1/2-octave intervals ranging from 0.25 to 8 kHz. One ear was chosen for ASSR testing, based on behavioral audiogram configurations, as stated above. Starting intensities for ASSR testing were 40 or 60 dB nHL (randomized between subjects). ASSR thresholds for the multiple-stimulus technique were bracketed using 20-dB steps and then 10-dB up-down steps. If, after averaging at least five sweeps, a response was indicated to be significantly present, then the stimulus intensity was decreased in 20-dB steps until a no-response was obtained for at least three out of four carrier frequencies. Intensity was then increased to a level that would provide estimation of the greatest number of thresholds. The remaining levels were then tested to fill in the gaps. Stimulus intensities did not go below 0 dB nHL or exceed 90 dB nHL. A 10-dB down/10-dB up search procedure was performed for the single-stimulus condition. ASSR thresholds were defined as the lowest intensity where a response was present and a no-response was obtained at 10 dB lower. False-positive responses were classified as statistically significant responses occurring at levels where no significant responses occurred at both 10 and 20 dB higher. False-negative responses were classified as non-significant responses where a significant response was identified at both 10 dB lower and 10 dB higher. There were false-positive and false-negative responses in 13 of 660 assessments (2.0%). In three recordings (two subjects), significant responses (one at 2000 Hz and two at 4000 Hz) could not be obtained at any of the test levels (0–90 dB nHL). Therefore, thresholds were arbitrarily defined as 100 dB nHL (i.e. 10 dB above the highest intensity tested). If there were significant responses down to 0 dB nHL, the threshold was considered to be 0 dB nHL. Excluding these arbitrarily set thresholds of 0 and 100 dB nHL did not change the statistical results. Therefore, they were included in the analysis.
Statistical analyses

Based on their audiogram configurations, participants’ results were placed in one of two groups: (A) steep-sloping $\geq 30$ dB/octave) hearing impairments ($n=18$); or (B) flat/shallow-sloping (<30 dB/octave) hearing impairments ($n=13$). Steep-sloping impairments ranged from 30 to 65 dB/octave (mean 43±11 dB/octave), and shallow-sloping impairments ranged from 0 to 25 dB/octave (mean 15±9 dB/octave). For the multipleASSR condition, six subjects had incomplete data, so thresholds could not be assessed for all test frequencies (see Figure 2).

Results were statistically analyzed to examine four important issues: (1) behavioral audiogram estimation using multipleASSR thresholds; (2) place specificity of the multipleASSR method; (3) possible masking effects when presenting iso-intense multiple-stimuli; and (4) recording time for the monotic multipleASSR method in estimating thresholds for hearing-impaired subjects.

ANALYSES OF ESTIMATION OF THE BEHAVIORAL AUDIOMGRAM

To evaluate the sensitivity of the multipleASSR method in estimating behavioral thresholds, a two-way repeated-measures analysis of variance (ANOVA) was used to compare difference scores (multipleASSR thresholds minus behavioral thresholds) for both groups across four frequencies (500, 1000, 2000 and 4000 Hz). Huynh–Feldt epsilon correction factors for degrees of freedom were used to evaluate significant ANOVA results (Huynh & Feldt, 1976). Results from the ANOVA were considered significant if $p<0.01$. Newman–Keuls post hoc comparisons were performed only for significant main effects and interactions. Post hoc comparisons were considered significant if $p<0.05$.

Pearson product–moment correlation coefficients were used to assess the relationship between behavioral and multipleASSR thresholds for each carrier frequency, as well as for results for all frequencies combined. Using a $t$-test, correlation coefficients were compared to a mean of zero. Results from these tests were considered significant if $p<0.01$.

Two methods were used to test the ability of multiple ASSRs to estimate the configuration of behavioral audiograms. Similar methods have been described by Perez-Abañalo et al (2001). First, a within-subject Pearson product–moment correlation coefficient was determined for each individual. The $X$ and $Y$ values were the multipleASSR and behavioral thresholds for each carrier frequency (500, 1000, 2000 and 4000 Hz). Only subjects’ data with ASSR thresholds at three or more frequencies were used to compute individual correlations. Individual correlation coefficients were used as dependent variables in a Student $t$-test, and tested for significance against a mean of zero. Also, individual correlation coefficients were separately assessed for significance. These statistical results indicated the ability of multipleASSRs to estimate the configuration of an individual’s behavioral audiogram.

Second, to compensate for the systematic elevation of multipleASSR thresholds over behavioral thresholds (Perez-Abañalo et al, 2001), Z-scores for multipleASSR and behavioral thresholds ($Z_b$ and $Z_a$) for each carrier frequency (500, 1000, 2000 and 4000 Hz) were calculated using a Z transform, as follows:

$$Z\text{-score} = \frac{\text{individual threshold} - \text{mean threshold}}{\text{standard deviation}}$$

This normalized the data so that ASSR thresholds could be compared with the behavioral thresholds. Subtracting the Z-scores ($Z_a$ minus $Z_b$) for each subject at each frequency yielded a Z-score difference value. Z-score differences were then compared across carrier frequencies using a one-way repeated-measures ANOVA. ANOVA results were considered significant if $p<0.01$.

ANALYSIS OF PLACE SPECIFICITY

To assess place specificity, difference scores (multipleASSR thresholds minus behavioral thresholds) were calculated for frequencies within the steepest-sloping portion of the audiogram with the greatest behavioral threshold (i.e. ‘frequency of interest’, see above). For example, if behavioral thresholds were 10, 20, 60 and 70 dB HL for respective frequencies of 500, 1000, 2000, and 4000 Hz, then a difference score was calculated at 2000 Hz. For each group, individual difference scores were combined across different frequencies, because different subjects had audiograms where the steepest slope occurred at different frequencies. A Student $t$-test for independent samples was used to compare these difference scores between groups A and B. Results were considered significant if $p<0.01$.

ANALYSES OF MASKING ISSUES USING MULTIPLE ISO-INTENSE AM TONES

The possibility of masking of multiple ASSRs to high-frequency AM tones (e.g. 4000 Hz) by simultaneously presenting lower-frequency stimuli (e.g. 500 Hz) was assessed by comparing multiple- and singleASSR thresholds for high frequencies for subjects with moderate-to-severe hearing impairments. Subjects with moderate-to-severe hearing impairments were chosen for this analysis because they would theoretically have the most masking, due to their poorer cochlear tuning. ASSR thresholds were combined over 1000 Hz ($n=1$), 2000 Hz ($n=3$), and 4000 Hz ($n=6$). Additionally, the relationship between multiple- and singleASSR thresholds was determined from a Pearson product–moment correlation coefficient, and was considered significant if $p<0.01$.

ANALYSES OF RECORDING TIME

Total recording times were estimated from the total number of sweeps that were recorded to obtain thresholds for four frequencies in one ear using the multipleASSR method. The total number of sweeps was multiplied by the time per sweep (16.384 s/sweep) to give a total recording time per subject. Only subject data that included thresholds for all four frequencies were included in the average of total recording times ($n=23$). Because it may require more time to obtain ASSR thresholds than flat/shallow-sloping audiograms in steep-sloping hearing impairments, recording times between group A and B were assessed using a Student $t$-test for independent samples. Results were considered significant if $p<0.01$.

Results

**MultipleASSR estimation of behavioral thresholds**

Figure 1 shows the single and multiple ASSRs used to assess hearing thresholds in an individual (subject 1) with a steep-sloping severe hearing impairment. Mean amplitude spectra at various stimulus intensities are shown for the multiple-stimulus
condition, for the 1000-Hz single AM tone, and for the 2000-Hz AM tone. Significant ASSRs occur at the modulation frequencies of 77, 85, 93 and 101 Hz for AM tones of 500, 1000, 2000 and 4000 Hz, respectively. Four significant ASSRs can be seen for the multiple-stimulus condition at 80 dB nHL. At 70 dB nHL, there is no significant response for the 4000-Hz AM tone. Thus, the multiple-ASSR threshold for the 4000-Hz AM tone is determined to be 80 dB nHL. This is equal to the subject’s behavioral pure-tone threshold. For the 2000-Hz AM tone in the multiple-stimulus condition, ASSRs are significant down to 70 dB nHL and non-significant at 60 dB nHL. The threshold is, therefore, 70 dB nHL, and is at the same level measured behaviorally. There are significant ASSRs for the 1000-Hz AM tone in the multiple-ASSR condition from 80 to 10 dB nHL, with a non-significant response at 0 dB nHL. As for the 500-Hz AM tone in the multiple-stimulus condition, significant ASSRs

![Subject 1](image)

**Figure 1.** ASSR amplitude spectra from subject S1 for the monotic multiple-ASSR (left panel) and single-ASSR (right panel) methods. Spectra are plotted only for 70–110 Hz. Stimulus intensities (dB nHL) are specified to the left of the amplitude spectra. Closed arrowheads designate significant ASSRs at modulation frequencies of 77, 85, 93 and 101 Hz for carrier frequencies of 500, 1000, 2000 and 4000 Hz, respectively. ASSR thresholds were determined to be at the level with a significant response and a no-response at 10 dB lower. Behavioral and ASSR thresholds are tabulated at the bottom.
Figure 2. Behavioral, multiple-ASSR and single-ASSR thresholds at 500, 1000, 2000 and 4000 Hz are plotted for each subject. Based on their audiograms, subjects are divided into group A (≥30 dB/octave slope) and group B (<30 dB/octave slope). Subject identifiers are in the top right-hand corner of each graph.
Table 1. Mean behavioural thresholds, multiple-ASSR thresholds and difference scores by frequency for group A, group B, and both groups combined.

<table>
<thead>
<tr>
<th>Measure</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M±SD n</td>
<td>M±SD n</td>
<td>M±SD n</td>
<td>M±SD n</td>
</tr>
<tr>
<td>Group A: steep-sloping hearing impairment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Behavioral</td>
<td>14±8 18</td>
<td>23±17 18</td>
<td>46±26 18</td>
<td>67±16 18</td>
</tr>
<tr>
<td>Multiple ASSR</td>
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<td>32±18 16</td>
<td>61±24 16</td>
<td>68±15 17</td>
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<tr>
<td>Difference score</td>
<td>13±13 13</td>
<td>8±10 16</td>
<td>12±10 16</td>
<td>1±10 17</td>
</tr>
<tr>
<td>Group B: flat/shallow-sloping hearing impairments</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Behavioral</td>
<td>32±23 13</td>
<td>35±22 13</td>
<td>45±24 13</td>
<td>56±25 13</td>
</tr>
<tr>
<td>Multiple ASSR</td>
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<td>42±20 13</td>
<td>47±16 11</td>
<td>56±19 11</td>
</tr>
<tr>
<td>Difference score</td>
<td>15±13 13</td>
<td>7±8 13</td>
<td>7±11 11</td>
<td>5±9 11</td>
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<td></td>
<td></td>
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<tr>
<td>Behavioral</td>
<td>21±18 31</td>
<td>28±20 31</td>
<td>46±25 31</td>
<td>62±21 31</td>
</tr>
<tr>
<td>Multiple ASSR</td>
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<tr>
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<td>14±13 26</td>
<td>8±9 29</td>
<td>10±10 27</td>
<td>3±10 28</td>
</tr>
</tbody>
</table>

M=mean; SD=standard deviation; n=sample size.
*Measured in dB HL. b Measured in dB nHL. c Calculated in dB.

are recorded down to 0 dB nHL. The threshold is, therefore, considered to be 0 dB nHL. Single AM tone thresholds for 1000 and 2000 Hz are 10 and 80 dB nHL, respectively. Behavioral, multiple-ASSR and single-ASSR thresholds for subject S1 are tabulated at the bottom of Figure 1 and graphically presented in Figure 2.

Figure 2 depicts behavioral, multiple-ASSR and single-ASSR thresholds for each subject. They are grouped according to the slopes of their behavioral hearing impairments. Thresholds for subjects in group A, who have steep-sloping (≥30 dB/octave) impairments, are shown in the first 18 audiograms, whereas thresholds for subjects in group B, who have flat/shallow-sloping (<30 dB/octave) impairments, are shown in the lower 13 audiograms. Mean behavioral thresholds, multiple-ASSR thresholds and difference scores (multiple-ASSR minus behavioral threshold) are listed in Table 1 for groups A and B, as well as for the groups combined.

Multiple-ASSR thresholds are within 20 dB of behavioral thresholds in 81%, 93%, 93% and 100% of the subjects for frequencies of 500, 1000, 2000 and 4000 Hz, respectively (Table 2). A two-way ANOVA (group x frequency) of difference scores reveals no significant differences between group A and B when averaged across frequency (F=0.12; df=1, 21; p=0.729), with no significant interaction between group and frequency (F=1.87; df=3, 63; p=0.144). ANOVA results reveal a significant effect of frequency, averaged over groups A and B (F=5.59; df=3, 63; p=0.002). Post hoc analysis shows that the difference score for 4000 Hz is significantly (p<0.05) smaller than those for 500, 1000 and 2000 Hz.

Pearson product–moment correlations show significant (p<0.001) relationships (r=0.75-0.89) between multiple-ASSR thresholds and behavioral thresholds for each carrier frequency and for all carrier frequencies combined. Figure 3 depicts the relationship between behavioral and multiple-ASSR thresholds. Regression equations, sample size (n) and correlation coefficients (r) are presented in Figure 3.

To provide an indication of how well the configurations of the multiple-ASSR and behavioral audiogram match, correlations between multiple-ASSR and behavioral thresholds were determined across frequency for each individual. The mean correlation, averaged across subjects, is r=0.83±0.28. A Student t-test of the average individual correlations, testing the null hypothesis that thresholds are unrelated (i.e. a mean of zero), shows a significant relationship between behavioral and multiple-ASSR thresholds (t=4.05; df=24; p<0.001). Moreover, 35% (9/26) of the individual correlations are greater than 0.99, and have probabilities less than <0.01 of being different from a mean of zero; 73% (19/26) are greater than 0.83, and have probabilities less than 0.05; 81% (21/26) are greater than 0.78, and have probabilities less than 0.10; and 85% (22/26) are greater than 0.66, and have probabilities less than 0.15.

Comparing across carrier frequencies, the Z-score differences (Za minus Zb) constitutes another statistical method used to indicate the correspondence of multiple-ASSR and behavioral audiogram configurations (Perez-Abalo et al, 2001). Mean Z-score differences are ~0.022±0.597, ~0.016±0.477, 0.058±0.407 and 0.036±0.497 standard deviations for carrier frequencies of 500, 1000, 2000 and 4000 Hz, respectively. Thus, Z-score differences are small, with none exceeding ±1.23 standard deviations.

Table 2. Percentage of subjects’ difference scores by frequency.

<table>
<thead>
<tr>
<th>Range</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
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<tr>
<td>30 &lt; Diff ≤ 40</td>
<td>12</td>
<td>4</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Diff=difference score (multiple-ASSR minus behavioral thresholds).
Figure 3. Graphical representation of linear regression analysis comparing multiple-ASSR thresholds with behavioral pure-tone thresholds for frequencies of 500, 1000, 2000 and 4000 Hz, as well as for data combined across all carrier frequencies (middle plot). Regression equations, sample size \((n)\) and correlation coefficient \((r)\) are given in the upper left-hand corner of each graph. Overlapping data have adjusted by \(\pm 1\) dB in both directions to resolve all points in the plots. Arrows designate thresholds that were set at 10 dB above maximum testing levels. The regression equation is as follows: \(y = mx + b\), where \(y\) is the behavioral threshold, \(m\) is the slope of the regression, \(x\) is the ASSR threshold, and \(b\) is the \(y\)-intercept.
Results from the ANOVA show no significant difference between Z-score differences compared across carrier frequencies ($F=0.167; df=3, 69; p=0.918$).

**Place specificity of the multiple-ASSR method**

Place specificity of the multiple-ASSR method is assessed by comparing difference thresholds (multiple-ASSR minus behavioral) at the frequency with the highest behavioral threshold and the greatest slope (i.e. frequency of interest) between groups A ($\geq 30 \text{dB/octave slopes}$) and B ($<30 \text{dB/octave slopes}$). Results from three of 18 (17%) subjects (S2, S5, and S11) in group A show that multiple ASSR underestimate behavioral thresholds by 5–20 dB at the frequency with the greatest slope (i.e. frequency of interest). The other 15 subjects in group A have multiple-ASSR thresholds at the frequency of interest that are 0–20 dB higher than behavioral thresholds. The mean difference threshold for group A is $2.5\pm10.5 \text{dB}$ ($n=18$), and that for group B is $5.0\pm5.4 \text{dB}$ ($n=13$). Group A shows a 2.5-dB smaller difference between behavioral and multiple-ASSR thresholds compared to group B. However, statistical comparison using a t-test for independent samples reveals that this difference is not significant ($t=-0.786; \text{df}=26; p=0.438$).

**Masking issues when using multiple iso-Intense AM tones**

Simultaneously presenting multiple iso-intense AM tones may cause ASSRs to high-frequency stimuli (e.g. 4000 Hz) to be masked by low-frequency stimuli (e.g. 500 Hz). This hypothesis is tested by comparing single- and multiple-ASSR thresholds for moderate-to-severe hearing impairments at high frequencies, combined across 2000 Hz ($n=3$) and 4000 Hz ($n=7$). For the single- and multiple-stimulus conditions, mean thresholds are 63±9 and 64±14 dB nHL, respectively. A repeated-measures Student t-test reveals no significant difference between stimulus conditions ($t=-0.318; \text{df}=9; p=0.758$). Furthermore, the Pearson product-moment correlation between these single- and multiple-ASSR thresholds is 0.72, which is not significant ($F=8.652; \text{df}=1, 8; p=0.016$). Subtracting behavioral thresholds from single-ASSR and multiple-ASSR thresholds yields mean difference scores equaling 6±11 dB and 5±12 dB, respectively.

**Recording time**

The recording times needed to obtain four thresholds (500, 1000, 2000 and 4000 Hz) using the multiple-ASSR method are estimated from the total number of sweeps recorded. Mean total recording times for groups A and B are 49±13 and 44±14 min, respectively. There is no significant difference in recording times between groups A and B ($t=0.935; \text{df}=21; p=0.360$). The distribution of recording times is shown in Table 3. For 78% of the subjects, thresholds for four frequencies (in one ear) are obtained within 60 min.

**Discussion**

**Multiple-ASSR estimation of behavioral thresholds**

The audiograms in Figure 2 suggest that the multiple-ASSR method can accurately predict both the degree and configuration of the behavioral audiogram. Similar conclusions can be drawn from the single-ASSR results reported by Aoyagi et al. (1999) and from the multiple-ASSR results reported by Lins et al. (1996). Quantitative analyses from the present study confirm this impression.

The results from the present study are similar to those reported from previous investigations assessing the sensitivity of either single- or multiple-ASSR methods in estimating behavioral thresholds in subjects with sensorineural hearing impairments (Table 4). ASSR thresholds are, on average, between 3 and 17 dB higher than behavioral thresholds, which indicates good sensitivity for the ASSR method. It is important to note that some thresholds (16/110) were overestimated by 30–40 dB (see Table 2). Although this is an undesirable result with regard to using ASSRs to assess threshold, most of the overestimated thresholds were for the 500-Hz stimulus. As discussed below, the stimulus protocols for 500-Hz AM tones might not be optimal.

Whether stimuli are presented separately to one ear (i.e. monotic single-stimulus condition) or multiple-stimuli are presented simultaneously to one (i.e. monotic multiple-stimulus condition) or both ears (i.e. dichotic multiple-stimulus condition) does not seem to make a difference in estimating hearing thresholds. The results from the present study confirm this, by revealing that differences in difference scores of 6 and 5 dB between the single-stimulus and multiple-stimulus conditions are neither statistically nor clinically significant.

Table 4 also presents grand means, standard errors of the means and 95% confidence limits for the difference scores from a meta-analysis performed on results from the seven studies presented in Table 4. All calculations within the meta-analysis are appropriately weighted for each study’s sample size (Howell, 1997). The results from the meta-analysis show that ASSR thresholds are 6–10 dB higher than behavioral thresholds, and indicate that ASSRs provide accurate estimates of behavioral thresholds. Moreover, these small difference scores support the idea that ASSRs can be useful for audiometric evaluation of hearing thresholds in subjects with sensorineural hearing impairments.

There is some concern regarding the sensitivity of ASSRs at 500 Hz (Lins et al, 1996; Perez-Abalo et al. 2001). Lins et al (1996) revealed that ASSR thresholds for 500 Hz were significantly elevated compared to thresholds at frequencies of 1000-4000 Hz in subjects with normal hearing. This pattern of results is similar to that for tone-evoked ABRs (Stapells, 2000). Perez-Abalo et al (2001) also revealed that the elevated 500-Hz threshold was age-dependent, with infants having greater thresholds. Perez-Abalo et al (2001) showed similar results, with higher ASSR thresholds at 500 Hz than at other frequencies, but this was also the case for behavioral thresholds. An ANOVA comparing difference scores across frequencies was not performed.
Table 4. Summary of difference scores from the present study and previous literature, and a meta-analysis.

<table>
<thead>
<tr>
<th>Study and ASSR method</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diff</td>
<td>r</td>
<td>N</td>
<td>Diff</td>
</tr>
<tr>
<td>Present Study</td>
<td>14±13</td>
<td>0.75</td>
<td>26</td>
<td>8±9</td>
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<tr>
<td>Monotonic multiple</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aoyagi et al (1999)</td>
<td>–</td>
<td>0.73</td>
<td>34</td>
<td>4±13</td>
</tr>
<tr>
<td>Monotonic single</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimitrijevic et al (2002)</td>
<td>13±11</td>
<td>0.85</td>
<td>31</td>
<td>5±8</td>
</tr>
<tr>
<td>Dichotic multiple</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lins et al (1996)a</td>
<td>9±9</td>
<td>0.72</td>
<td>10</td>
<td>13±12</td>
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<tr>
<td>Monotonic multiple</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perez-Abalo et al (2001)a</td>
<td>13±15</td>
<td>0.70</td>
<td>80</td>
<td>7±15</td>
</tr>
<tr>
<td>Dichotic multiple</td>
<td></td>
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</tr>
<tr>
<td>Picton et al (1998)b</td>
<td>17±8</td>
<td>0.68</td>
<td>32</td>
<td>13±8</td>
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<tr>
<td>Sound-field multiple</td>
<td></td>
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</tr>
<tr>
<td>Ranee et al (1998)b</td>
<td>6±7</td>
<td>0.97</td>
<td>129</td>
<td>4±6</td>
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<tr>
<td>Monotonic single</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meta-Analysisb</td>
<td>10±0.6</td>
<td>–</td>
<td>308</td>
<td>6±0.5</td>
</tr>
<tr>
<td>All methods combined</td>
<td>(95% confidence interval)</td>
<td>(9.2–11.6)</td>
<td>308</td>
<td>(4.6–6.7)</td>
</tr>
</tbody>
</table>

Dashes indicate that data were not reported or calculated. Carrier frequencies are given in Hz. Diff = mean ± one standard deviation for difference scores (ASSR minus behavioral thresholds). r = correlations.

*aIncludes data from children. bGrand means ± standard error of the mean and 95% confidence intervals given in parentheses for difference scores appropriately averaged over the seven studies presented above.

by Perez-Abalo et al (2001); however, our post hoc analysis of their results reveals that the difference score at 500 Hz is statistically greater than that at 4000 Hz (t=3.26; df=78; p=0.002). The 500-Hz grand mean difference scores from the meta-analysis are 3–4 dB higher than at any of the other carrier frequencies (Table 4). Additionally, the 95% confidence intervals for difference score for the 1000-4000-Hz carrier frequencies overlap with each other but do not overlap with the confidence interval for 500 Hz. The 4000-Hz and 500-Hz confidence intervals are remarkably close. These results suggest that there is a lower sensitivity for ASSRs to 500-Hz AM tones compared to ASSRs evoked by high-frequency stimuli. Although these differences are statistically significant, a 3–4 dB difference in sensitivity is not clinically relevant. Most importantly, grand mean difference scores for all carrier frequencies have standard errors that are quite low (±1 dB) and 95% confidence intervals that are quite narrow (ranging within ±3.5 dB). This indicates reasonably consistent threshold evaluations across a large number of subjects. Furthermore, results from the present study and Lins et al (1996) show that difference scores are not significantly different between carrier frequencies for subjects with hearing impairments. This is also the case for subjects with normal hearing (Herdman & Stapells, 2001).

While their results show that difference scores are not significantly different across carrier frequencies, Lins et al (1996) speculated that elevated absolute ASSR thresholds at 500 Hz might result from a greater jitter in the neural synchrony in response to a 500-Hz AM tone compared to higher-frequency stimuli. Although this may be the case, it is also possible that studies may be using more optimal stimulus parameters, such as optimal modulation frequencies, for the higher-frequency stimuli than for 500 Hz.

Even though statistical results conflict between studies (Dimitrijevic et al, 2002; Lins et al, 1996; Perez-Abalo et al, 2001), most results show that difference scores are not substantially different between carrier frequencies, and that there are respectable (<20 dB) threshold sensitivities for ASSRs to carrier frequencies between 500 and 4000 Hz. These results indicate there is little concern about using ASSRs, evoked by AM tones of 500–4000 Hz, to clinically assess air conduction hearing thresholds of subjects with normal or impaired hearing.

Correlations from the present study show significant relationships between multiple-ASSR and behavioral thresholds for all carrier frequencies. Similar correlations, listed in Table 4, have been reported from other studies (Aoyagi et al, 1999; Dimitrijevic et al, 2002; Lins et al, 1996; Perez-Abalo et al, 2001). There are notable inconsistencies, such as the low correlations (0.54-0.68) in the Picton et al (1998) study, and the very high correlations (0.97-0.99) in the Ranee et al (1998) study. Such discrepancies could result from different stimulus techniques. For example, a monotic single-stimulus condition was used in the Ranee et al (1998) study, whereas a binaural (sound-field) presentation of multiple AM tones through hearing aids was used in the Picton et al (1998) study. Most other investigations have reported correlations between 0.70 and 0.95, which indicate a good relationship between ASSR and behavioral thresholds.

Along with providing good sensitivity and moderate-to-high correlations across subjects, the multiple-ASSR technique must accurately estimate the configuration of the behavioral audiogram for individuals. By testing the difference between standardized vectors for behavioral and multiple-ASSR thresholds, Perez-Abalo et al (2001) showed that differences in audiogram configuration are not statistically different between behavioral and multiple-ASSR methods. However, most subjects had flat

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configurations of their audiograms. We therefore tested subjects with a variety of audiogram configurations to objectively assess (using the same statistical methods) the ability of multiple-ASSR thresholds to match behavioral audiograms. The results of the present study show that the differences in Z-scores are near zero, and thus are not significantly different, indicating that there are no differences in audiogram configurations between behavioral and ASSR methods. To further confirm this, individual correlations were calculated, and again showed that the differences between audiogram estimates are not significant. These results indicate that multiple ASSRs can accurately predict the configuration of the behavioral audiogram.

**Place specificity of the multiple-ASSR method**

Place specificity of the multiple-ASSR method has been recently shown for normal-hearing subjects (Herdman et al., 2002; John et al., 1998). The results of Herdman et al. (2002) show that bandwidths for multiple ASSRs to 60 dB SPL AM tones (500–4000 Hz) are approximately 1 octave wide and centered within 1/4 octave of the stimulus frequency. Although there is reasonable place specificity for subjects with normal hearing, subjects with a steep-sloping hearing impairment (≥30 dB/ octave) may have adjacent frequency regions undesirably contributing to the ASSR. In the present study, an indication of the place specificity for the multiple-ASSR method was determined by investigating whether there is an underestimation of the highest threshold at a frequency within the steepest-sloping part of the audiogram. For example, Picton et al. (1979) and Stapells et al. (1985) reported that brief-tone ABRs underestimate behavioral thresholds in subjects with steep-sloping hearing impairments because of the spectral splatter of the brief tones stimulating regions with better hearing sensitivity. They showed that this underestimation can be reduced if “notched” noise is used to mask the regions responding to this splatter. Purdy & Abbas (2002) investigated the place specificity of the tone ABR in subjects with sensorineural hearing impairments and showed that, for most subjects with steep-sloping hearing losses, the notch-evoked ABR did not underestimate behavioral thresholds. The results from the present study similarly show that, for most subjects (83%) with steep-sloping hearing losses, the multiple-ASSRs to AM tones do not underestimate behavioral thresholds. Furthermore, ASSR thresholds for group A (≥30 dB/octave slopes) are, on average, 2.5 dB greater than behavioral thresholds. Moreover, for subject S1, who has a very steep-sloping loss (45- dB drop between 1500 and 2000 Hz), there was no underestimation of the behavioral threshold when using the multiple-ASSR method. This is in contrast to results for one subject in the study by Purdy & Abbas (2002), who had a very steep-sloping (45-dB drop between 3000 and 4000 Hz) hearing loss, showing that the behavioral threshold at 4000 Hz is largely underestimated by brief-tone ABRs because of better hearing at 3000 Hz. Although neither multiple ASSRs nor tone-evoked ABRs underestimate hearing thresholds in subjects with steep-sloping hearing losses, there may be a difference when testing subjects with very steep-sloping impairments. Results from the current study suggest that the multiple-ASSR method may have the advantage, compared to the brief-tone ABR technique, of not requiring masking procedures to obtain frequency-specific thresholds for subjects with very steep-sloping hearing impairments. Furthermore, there is no difference between group A and group B thresholds, which indicates that multiple ASSRs were able to accurately predict thresholds in subjects whether or not they had steep-sloping hearing impairments. The results from the present study confirm that there is good place specificity for ASSRs in subjects with sensorineural hearing impairments, and that they are in agreement with results presented for normal-hearing listeners (Herdman et al., 2002).

**Masking issues when using multiple iso-Intensity AM tones**

The concern about masking high-frequency (e.g. 4000 Hz) ASSRs by simultaneously presenting a lower-frequency stimulus (e.g. 500 Hz) is not supported by the present data. There is no significant difference in thresholds (63 versus 64 dB nHL) between single- and multiple-ASSR methods for subjects with moderate-to-severe hearing impairments. This is in contrast to the results for a few subjects reported by Picton and co-workers (Dimitrijevic et al., 2002; Picton et al., 1998). Picton et al. (1998) proposed this masking problem because a few subjects showed more accurate threshold estimates at 2000 and 4000 Hz with the single-stimulus method than with the multiple-stimulus method. Dimitrijevic et al. (2002) also provided some evidence for possible masking from a limited number of subjects (n=5), showing that mean difference scores (ASSR minus behavioral thresholds) for the single-ASSR method (9 dB) was lower than for the multiple-ASSR method (21 dB). For a subpopulation of 10 subjects in the current study used to assess the possibility of masking, difference scores were 6 and 5 dB for the single- and multiple-ASSR methods, respectively. Results from the present study of a larger sample of subjects (n=10) with moderate-to-severe hearing impairments indicate that there is insufficient evidence to support the null hypothesis that inclusion of low-frequency (i.e. 500 or 1000 Hz) AM tones in the multiple-stimulus method causes masking of ASSRs to higher-frequency stimuli (i.e. 2000 or 4000 Hz).

In order to reduce recording time, the current practice of presenting multiple-stimuli at the same intensity for recording ASSRs may be modified to simultaneously presenting carrier frequencies at different intensities. Thus, concerns about masking may arise for this multiple-intensity (MINT) method when testing subjects with hearing impairments, especially for those with reverse-sloping audiograms. At least for subjects with normal hearing, John et al. (2002) showed that presenting 500- and 4000-Hz AM tones at 10–20 dB higher than the 1000- and 2000-Hz AM tones did not significantly change amplitudes of responses to the 1000- and 2000-Hz stimuli. The MINT technique may be even faster than the current iso-intensity method of recording multiple-ASSRs, thus adding to the overall efficiency of ASSRs in assessing hearing thresholds.

**Recording time**

Recording times estimated from the total number of sweeps revealed that thresholds for four frequencies could be obtained within 60 min for 78% (18/23) of the subjects. The present study's mean recording time of 47 min for obtaining four frequency-specific thresholds from subjects with varying degrees of hearing impairments is within practical limits for assessing hearing in hard-to-test patients. This mean recording time is substantially longer than the 21 min reported by Perez-Abalo et al. (2001). However, this may be a result of a lower number of intensities needed to bracket the flat audiograms of most subjects.
tested in the study by Perez-Abalo et al (2001). Additionally, this
discrepancy in recording times may be further compounded by the
fact that the present study uses a more strict noise criterion for
determining a "no-response", which required averaging until the
surrounding EEG noise was less than 10 nV. In the study by
Perez-Abalo et al (2001), averaging stopped after a maximum of
24 sweeps of 12.6 s (i.e. after 5 min). Stopping after 24 sweeps
may have reduced recording time, but some recordings may have
substantial EEG noise that may conceal a significant response,
thereby elevating threshold. Nevertheless, the less strict stopping
criterion used by Perez-Abalo et al (2001) did not dramatically
affect the sensitivity of the multiple-ASSR threshold in predicting
behavioral thresholds, as indicated by the difference scores (see
Table 4).

The results from the present study demonstrate that, in a
realistic amount of time, the monotonous (one-ear) multiple-ASSR
method can be useful for measuring thresholds in individuals
with hearing impairments. Furthermore, if a subject's audiogram
configuration is similar between ears, assessing both ears simulta-
aneously using ASSRs would provide double the information,
with only a minor increase in recording time.

Conclusion

The results from this study confirm previous reports showing
that the multiple-ASSR method is an accurate and sensitive
predictor of the behavioral audiogram in patients with a wide
range of sensorineural hearing impairments. Furthermore, an
objective analysis of the threshold data revealed that the
configuration of an individual's behavioral audiogram can be
matched using the multiple-ASSR technique. Given the lack of
underestimation of elevated behavioral thresholds at the
frequency edge of the steep-sloping impairment, ASSR thresholds
for one frequency do not appear to be affected by better hearing
at other frequencies. The results presented here indicate no
masking of high-frequency ASSRs by concomitant presentation
of lower frequencies. In summary, these results provide good
evidence for the usefulness of the multiple-ASSR technique for
predicting behavioral thresholds to air-conducted stimuli in
patients with sensorineural hearing impairments who do not
provide reliable behavioral results, as is the case with infants
under the age of 6 months.

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References

Optimal modulation frequency for amplitude-modulation following response