

Anna Van Maanen\*  
David R. Stapells†

\*Audiology Unit, Workers'  
Compensation Board of British  
Columbia, Vancouver, British  
Columbia, Canada

†School of Audiology and Speech  
Sciences, The University of British  
Columbia, Vancouver, British  
Columbia, Canada

### Key Words

Multiple auditory steady-state  
response  
Slow cortical potential  
Sensorineural hearing impairment  
Threshold

## Comparison of multiple auditory steady-state responses (80 versus 40 Hz) and slow cortical potentials for threshold estimation in hearing-impaired adults

## Comparación de las respuestas auditivas múltiples de estado estable (80 vs 40 Hz) y de los potenciales corticales lentos en la estimación de umbrales en adultos con hipoacusia

### Abstract

This study evaluated the use of multiple auditory steady-state responses (ASSRs) and slow cortical potentials (SCPs) to estimate behavioural audiograms in adults for compensation cases. Two groups of 23 subjects were assessed using either 80 Hz or 40 Hz multiple simultaneous tones with carrier frequencies of 0.5, 1.0, 2.0, and 4.0 kHz. SCP thresholds for 0.5, 1.0, and 2.0 kHz were obtained for both groups. Mean evoked potential thresholds (dB HL) minus behavioural pure-tone thresholds (dB HL) difference scores were 5–17 dB for the 80 Hz group, 1–14 dB for the 40 Hz group, and 20–22 dB for the SCPs. Thresholds for 40 Hz ASSR were significantly closer to behavioural thresholds than were 80 Hz or SCP thresholds. SCP and 40 Hz ASSR audiogram estimates were obtained more quickly than the 80 Hz ASSR. Multiple 40 Hz ASSR is the method of choice for evoked potential threshold estimation in adults.

### Sumario

Este estudio evaluó el uso de las respuestas auditivas múltiples de estado estable (ASSR) y de los potenciales corticales lentos (SCP) para estimar en casos de compensación, los audiogramas comportamentales de adultos. Se realizaron pruebas en dos grupos de 23 sujetos utilizando tonos múltiples simultáneos a 80 ó 40 Hz con frecuencias portadoras de 500, 1000, 2000 y 4000 Hz. Se obtuvieron umbrales SCP para 500, 1000 y 2000 Hz en ambos grupos. Los umbrales promedio de potenciales evocados (dBHL) menos las respuestas tonales comportamentales se ubicaron entre 5 y 17dB para el grupo de 80 Hz, de 1 a 40 dB para el grupo de 40 Hz y de 20 a 22 dB para los SCP. Los umbrales de las ASSR de 40 Hz estuvieron significativamente más cercanos a los umbrales comportamentales que los de 80 Hz o los umbrales SCP. Los SCP y las ASSR-40 Hz se obtuvieron más rápido que las ASSR-80 Hz. Las ASSR múltiples de 40 Hz son el método de elección para la estimación de umbrales con potenciales evocados en adultos.

Means of objectively estimating hearing threshold are required for infants, children, and adults who cannot volunteer reliable behavioural responses. As well, they are necessary in adults involved in compensation cases who may not provide valid behavioural hearing thresholds. There are several auditory evoked potential (AEP) methods for estimating hearing thresholds. Transient AEPs, including auditory brainstem responses, middle latency responses, and slow cortical potentials, have all been used for threshold estimation. The auditory brainstem response (ABR) is widely used and is the current AEP method of choice for threshold estimation in infants and children (Stapells, 2000a). Recording the ABR to brief tones rather than clicks greatly enhances the frequency specificity, and thus the accuracy, of threshold estimation (Oates & Stapells, 1998; Stapells, 2000a, 2000b).

For the passively or actively alert adult population, the slow cortical potential (SCP) is considered to be the AEP measure of choice for threshold estimation (Hyde, 1994; Stach et al, 1994;

Stapells, 2002). This is in part due to the good frequency specificity of the response (Picton, 1991). The SCP has been used successfully for medico-legal and compensation cases (Adelman & Van Maanen, 2001; Alberti et al, 1987; Bonvier, 2002; Coles & Mason, 1984; Tsui et al, 2002). One potential disadvantage of the SCP is that, in many cases, including the Workers' Compensation Board of British Columbia Audiology Unit, it requires the subjective judgement of waveforms by a clinician.

The auditory steady-state response (ASSR) is an accurate means of estimating hearing thresholds (Picton et al, 2003). The first ASSR to be discovered and studied was the 40 Hz ASSR, which has been found to be useful in evaluating hearing sensitivity in adults as it is most robust on awake, alert subjects but is difficult to recognize in infants (Galambos et al, 1981; Levi et al, 1993; Picton, Vajsar et al, 1987; Picton et al, 2003; Plourde et al, 1991; Stapells et al, 1988; Stapells et al, 1984; Suzuki & Kobayashi, 1984). Amplitudes of ASSRs to amplitude-modulated (AM) tones at modulated frequencies (MFs) with rates of

70 to 110 Hz are more stable than those with MFs between 35 and 55 Hz for both infants and adults regardless of physiologic state, and are useful for threshold estimation for normal-hearing and hearing-impaired subjects (Aoyagi et al, 1999; Dimitrijevic et al, 2002; Levi et al, 1993; Herdman & Stapells, 2003; Pethe et al, 2001; Perez-Abalo et al, 2001; Picton et al, 1998; Picton et al, 2002; Picton et al, 2003; Rance & Rickards, 2002; Rance et al, 1995; Vander Werff et al, 2002).

An AEP that would provide a fast, accurate, and objective means of obtaining thresholds would be valuable. An ASSR technique has emerged in which multiple frequencies can be evaluated at once (Lins & Picton, 1995). A response is evoked with a stimulus comprised of multiple AM tones, at least one octave apart in frequency, modulated at different rates, and combined to form one stimulus for each ear, and presented to one or both ears (Dimitrijevic et al, 2002; Herdman & Stapells, 2001, 2003; John et al, 1998; Lins & Picton, 1995; Perez-Abalo et al, 2001; Picton et al, 2003). The multiple-stimulus ASSR appears to be advantageous over single-stimulus ASSR in that it enables evaluation of at least four frequencies for both ears simultaneously, resulting in faster threshold estimation compared to single-stimulus ASSR (Dimitrijevic et al, 2002; Herdman & Stapells, 2001, 2003; John et al, 1998; John et al, 2002; Lins & Picton, 1995; Perez-Abalo et al, 2001). Although more study is needed, the multiple ASSR is a promising tool for threshold estimation and for infants and children. In the future, the ASSR might replace the ABR as the AEP of choice.

An objective technique in cooperatively alert, passive adults, where thresholds for multiple frequencies could be obtained simultaneously, would be a welcome addition to the clinical test battery for clinicians involved in medico-legal or compensation cases. Medico-legal and compensation cases often require verification of behavioural pure-tone thresholds to rule out or confirm non-organic hearing loss (Alberti et al, 1987). At the British Columbia Workers' Compensation Board (WCB) Audiology Unit, 6–8% of clients evaluated demonstrated some degree of non-organic hearing loss (Adelman & Van Maanen, 2001). This figure is consistent with other studies (e.g. Alberti et al, 1987). Although the SCP is used successfully at the WCB Audiology Unit, the multiple ASSR is objective, requiring no subjective judgement by the clinician and thus might be advantageous over the SCP. However, the majority of studies using multiple ASSRs for threshold estimation have concentrated on 70–110 Hz modulation frequencies (MFs). However, previous research, suggests that using the 40 Hz MF is optimal for awake adults for evoking an ASSR (for review, see Picton et al, 2003). The current study investigates the accuracy and the time required for the multiple-stimulus ASSRs for threshold estimation in normal-hearing and hearing-impaired adults using MFs near 80 Hz and 40 Hz, and compares these to the SCP.

## Methods

### Subjects

Forty-six adult males participated in this study. Participants were divided into two similar groups of 23 subjects each, and were selected based upon several factors, including audiometric configuration and age. The 80 Hz group had thresholds determined using the 80 Hz multiple ASSR. The 40 Hz group had thresholds determined using the 40 Hz multiple ASSR. All

subjects, except one, underwent SCP testing. Both groups of 23 subjects were composed of males aged 45 to 80 years (i.e. they were typical of the WCB claimant population). No differences existed in the ages of the ASSR groups ( $t = 1.18$ ;  $df = 44$ ;  $p = .25$ ). An attempt was made to include subjects in each group with a wide range of thresholds at each frequency. Three in each group had normal thresholds. All hearing losses were sensorineural. There was no significant difference for hearing thresholds at any frequency between groups (Group main effect:  $F = 0.01$ ;  $df = 1, 44$ ;  $p = .92$ ; Group  $\times$  Frequency interaction:  $F = 0.09$ ;  $df = 3, 132$ ;  $p = .97$ ).

In addition to the 46 subjects participating in the study, there were an additional 23 subjects who were rejected. Of these, three were from the 40 Hz multiple ASSR group and twenty were from the 80 Hz multiple ASSR group. These subjects were rejected due to high noise in their electroencephalogram (EEGs). See Procedures section.

All participants underwent acoustic immittance testing on the day of testing and pure-tone behavioural threshold testing was completed within a month of the ASSR testing. SCP testing for most subjects was conducted within one month of the ASSR testing, with the exception of three subjects, whose SCP testing was conducted within three months of ASSR testing. For those subjects, behavioural thresholds were re-tested to ensure no change in hearing. The research was approved by the University of British Columbia Behavioural Research Ethics Board.

### Stimulus Parameters

Stimulus parameters for the multiple-stimulus ASSR were based on those previously reported by John et al (1998) and by Herdman and Stapells (2001, 2003). Stimuli were sinusoidal amplitude-modulated (AM) and frequency-modulated (FM) tones that were generated and presented by the Rotman MASTER research system (John & Picton, 2000) and were attenuated using the GSI 61 clinical audiometer. Air-conducted stimuli were presented to one ear through an ER-5A insert earphone. Stimuli for the 70–110 Hz (80 Hz) multiple ASSR consisted of sine waves at carrier frequencies of 0.50, 1.0, 2.0, and 4.0 kHz, 100% amplitude-modulated at frequencies of 77.148, 84.961, 92.773, and 100.86 Hz, respectively, as well as 20% frequency modulation. Modulation rates for the 36.7–45 Hz (40 Hz) multiple ASSR were 36.133, 39.062, 41.992, and 44.922 Hz for 0.50, 1.0, 2.0, and 4.0 kHz carrier frequencies. Modulation frequencies for the 40 Hz multiple ASSR were chosen based upon research by John et al (1998), which indicated that the modulation frequencies for different carrier frequencies may be separated as little as 4 Hz without affecting the response.<sup>1</sup> For both multiple ASSR conditions, modulation frequencies were employed so that each EEG recording section contained an integer number of carrier frequency cycles. The intensity of the tone varied from 0 to 100 dB HL. To avoid a temporary threshold shift, a conservative stimulus paradigm was used for 90 and 100 dB HL: ASSR stimuli exposure time was limited to a maximum of nine minutes and cochlea rest breaks were provided (three minutes stimulus on time, with equal off time).

<sup>1</sup>We carried out a pilot study of one subject with a 3 Hz separation and found an approximately 33% decrease in four frequencies compared to one carrier frequency with rates from 36 Hz (0.5 kHz) to 45 Hz (4 kHz). Thus four stimuli are more efficient than a single stimulus.

Stimulus parameters for SCP testing were based upon those previously reported by Hyde (1994). Air-conducted stimuli were presented to one ear through an ER-3A insert earphone. Stimuli for the SCP consisted of 60 ms tones at 0.5, 1.0, and 2.0 kHz. These frequencies were chosen due to the requirements of the *Workers Compensation Act* of British Columbia. The brief tone stimuli had a 10 ms rise/fall time with a 40 ms plateau for a total duration of 60 ms and were presented at a rate of 0.9 per second. As is normally done in the WCB Audiology Unit, the SCP stimuli were calibrated in dB eHL (estimated hearing level). Acoustic calibrations for 0 dB eHL were 31, 25, and 28 dB peak-to-peak equivalent SPL for the 0.5, 1.0, and 2.0 kHz 60 ms tones, respectively. An individual with a 20 dB eHL SCP threshold typically has a 20 dB HL pure-tone behavioural threshold (Adelman & Van Maanen, 2001). For this study, in order to be consistent with ASSR methods, acoustic levels for the SCP stimuli were subsequently converted to dB HL. The intensity of the SCP tonal stimuli varied from 0 to 100 dB eHL.

#### *Evoked Potential Recording Parameters and Analysis*

Equipment set-up and recording parameters for the ASSR were based on those previously reported by John et al (1998) and by Herdman and Stapells (2001, 2003). Three disk electrodes were placed on the subject's scalp on the vertex (non-inverting), on the nape of the neck (inverting), and on the forehead (ground). Impedance for all three electrodes was less than 5 kOhms at 10 Hz. The EEG was amplified 80,000 times for both the 40 Hz and 80 Hz ASSR and filtered using a bandpass of 30 to 250 Hz (12 dB/octave) for the 80 Hz ASSR, and 5 to 100 Hz (12 dB/octave) for the 40 Hz ASSR.

For the 80 and 40 Hz multiple ASSR, an EEG recording sweep of 16.38 seconds (sampling rate of 500 Hz), containing sixteen sections of 1.02 seconds each, was used. Artifact rejection limits were set at  $\pm 40 \mu\text{V}$  to eliminate potentials due to muscle or movement artifact. The ASSRs were analyzed in the frequency domain by Fast Fourier Transform (FFT). The FFT resolution was 0.083 Hz, spanning from 0 to 250 Hz. Amplitudes reported were measured from baseline to peak. Cosine onset phases were measured from the FFT in the range of  $-90$  to  $270$  degrees. Determination of significance was made by on-line analysis of the variance (F-statistic) of the FFT (Picton, Skinner et al, 1987). The *F*-ratio was computed between the response amplitude of the modulation frequency and the amplitude of the noise at surrounding frequency bins. A response was determined when the *F*-ratio of the signal to noise was significant at the  $p < .05$  level. No response was determined if the EEG background noise amplitude was low enough (see below) around the carrier frequency of interest and  $p \geq .05$ . ASSRs were assessed as present based upon whether the EEG amplitude at the MF of the modulated tone was significantly different from the background noise. The residual noise was determined by averaging the noise value in the 120 surrounding frequency bins, extending 4.98 Hz on either side of the MF. The circle radius (CR) represents the 95% confidence limits for the averaged noise (John & Picton, 2000). The recording was continued until the CR was less than 20 nV for the 80 Hz multiple ASSR (Dimitrijevic et al, 2002; Herdman & Stapells, 2003; Picton et al, 2005; Small & Stapells, 2005) or 60 nV for the 40 Hz multiple ASSR or until a significant SNR ( $p < .05$ ) was obtained, which ever occurred first (typically requiring twelve to 48 recording sweeps). The

criterion for 40 Hz multiple ASSR was determined based upon what is known about well-established recording parameters and analysis of the 80 Hz multiple ASSR. As previously stated, for the 80 Hz multiple ASSR, the CR must be less than 20 nV to be considered low enough for determination of the presence or absence of a near threshold response (Picton et al, 2005). The amplitude of the 40 Hz response is approximately three times as large as the 80 Hz response and the noise about two to three times the size (in subjects who were awake) (John et al, 1998). Therefore, we determined that the CR criterion could be three times as large (i.e. 60 nV) for the 40 Hz multiple ASSR.

Recording parameters for the SCP were based on those previously reported by Hyde (1994). Three disk electrodes were placed on the subject's scalp on the vertex (non-inverting), on the mastoid (inverting) and on the forehead (ground). Impedance for all three electrodes was less than 5 kOhms at 10 Hz. The EEG was amplified 100,000 times and filtered using a bandpass of 1 to 15 Hz. The time window used was 940 ms, including 250 ms pre-stimulus. Artifact rejection limits were set at  $\pm 51 \mu\text{V}$  to eliminate potentials due to muscle or movement artifact. Ten to 25 EEG recording sweeps (1.11 s/sweep) were averaged for each replication at each stimulus intensity, with more sweeps obtained near threshold.

The presence or absence of the SCP response was judged by experienced clinicians. The waveform had to be larger than the background EEG noise (as indicated by the pre-stimulus period) and at least two replications at threshold and two replications below threshold were required to assess replicability. The clinician also used morphology and latency of the waveform to aid in determining response presence. Morphology was judged based upon peak-to-peak amplitude of N1-P2, relative to the pre-stimulus baseline. Latency was judged based upon N1 and P2 occurring at approximately 100 and 175 ms. For the majority of the subjects (35/45), the SCP tester had no knowledge of the subject's behavioural pure-tone thresholds. SCP waveform analysis was performed only on data that were considered to be reliable as determined by the rejection rate and the observed physiological state of the client. If the rejection rate was over 50% or the subject exhibited EEG alpha rhythm, that particular waveform was not analyzed.

#### *Procedures*

The study involved one recording session of 1.5–3.5 hours or two recording sessions of 1–2 hours each (testing included behavioural, ASSR and SCP testing). All behavioural pure-tone testing was conducted first, using a modified Hughson-Westlake procedure. Participants relaxed in a comfortable reclining chair within a double-walled sound-attenuated booth during behavioural and electrophysiological measures. Participants were asked to sleep or relax during 80 Hz multiple ASSR testing. During the 40 Hz multiple ASSR testing, participants were asked to relax but were not allowed to sleep, as sleep reduces the amplitude of the 40 Hz ASSR (Jerger et al, 1986; Linden et al, 1985; Picton et al, 2003). For SCP testing, participants relaxed with eyes open, in a comfortable chair in a double-walled sound-attenuated booth. Participants were given the option of reading during the testing.

ASSR threshold for a specific carrier frequency was considered the lowest intensity at which a response was present and no

response was obtained at 10 dB below that intensity.<sup>2</sup> Responses were considered false positive when occurring at levels where there was no response 10 or 20 dB higher. Responses were considered a false negative when significant responses were obtained at two consecutive intensities below a level of no response. In this case, the lower of the two intensities was considered to be threshold.

ASSR threshold estimation procedures occurred as follows: the starting intensity was randomly selected at 40 or 60 dB HL. If, after five sweeps, the response was present at all frequencies, the stimulus intensity was decreased in 20 dB steps until no response was obtained at least at one frequency. If there was no response obtained at any frequency for 40 dB HL, the stimulus intensity was increased to 60 dB HL. If there was still no response, the intensity was increased in 10 dB steps until a response was obtained. A bracketing procedure with a 10 dB final step size was used. Subjects were excluded from the data pool if, after reinstruction regarding relaxation and repositioning, there were more than 20% rejects during recording at the starting intensity, or if noise floor could not be reduced close to the criterion after 48 sweeps.

SCP threshold estimation occurred as follows: starting intensity was selected at 62 dB HL (40 dB eHL) for 0.5 and 1.0 kHz and 72 dB HL (50 dB eHL) for 2 kHz. Order of test frequencies was 0.5, 1.0, then 2.0 kHz. If a response was present, the stimulus intensity was decreased in 10 dB steps until no response was obtained. If no response was obtained at 62 dB HL, the stimulus intensity was increased to 82 dB HL (60 dB eHL). If there was still no response, the intensity was increased in 10 dB steps until a response was obtained. A bracketing procedure with a 5 dB final step size was used.

#### Data Analyses

To compare the correspondence of the AEP (ASSR and SCP) thresholds to the behavioural thresholds, difference scores were calculated by subtracting the pure-tone behavioural thresholds (in dB HL) from the ASSR or SCP thresholds (in dB HL).

Estimated recording times were determined for both multiple ASSR and SCP. Estimated recording times for threshold evaluation for both 80 Hz and 40 Hz multiple ASSR were calculated using the total number of sweeps needed to obtain thresholds. For multiple ASSR, total estimated recording times were calculated using the total number of sweeps recorded to obtain thresholds for four frequencies for one ear. The total number of sweeps was multiplied by time per sweep (16.384 sec/sweep) to give an estimate of the total recording time per subject. For the SCP, estimated total recording times were determined using the total number of sweeps required to obtain thresholds for three frequencies for one ear. The total number of sweeps was multiplied by time per sweep (1.11 s/sweep). This was then converted to a four-frequency estimate to compare to the four-frequency multiple ASSR.

<sup>2</sup>The bracketing technique was used for threshold estimation with the exception of one subject at one frequency, where the intensity 10 dB below the response was not tested. In this case, threshold was estimated at the lowest recorded intensity rather than the intensity below (which was not recorded) based upon the borderline amplitude (63 nV) and  $p$ -value ( $p = .012$ ) of the recorded response.

#### Statistical Analyses

To evaluate the sensitivities of the 80 versus 40 Hz multiple ASSRs for estimating behavioural threshold, a mixed-model analysis of variance (ANOVA) with two factors was used: one between-subjects group factor (80- versus 40 Hz multiple ASSR group) and one within-subjects repeated-measures factor (carrier frequency: 0.50, 1.0, 2.0, and 4.0 kHz). To evaluate sensitivities of the multiple ASSR (80 and 40 Hz) and the SCP for estimating behavioural threshold, a mixed-model ANOVA with three factors was used: one between-subjects group factor (80 versus 40 Hz multiple ASSR group), and two repeated measures within-subjects factors: AEP test (ASSR versus SCP) and frequency (0.5, 1.0, and 2.0 kHz).

A mixed-model ANOVA was used to analyze the time (in minutes) required to estimate a four-frequency audiogram for one ear by each AEP, with one within-subjects factor (AEP test: ASSR versus SCP) and one between-subjects group factor (80 Hz versus 40 Hz group).

For all repeated measures ANOVAs, Huynh-Feldt epsilon correction factors for degrees of freedom were used when appropriate. Results of these ANOVAs were considered significant if  $p < .01$ . Newman-Keuls post hoc comparisons were performed for significant main effects and interactions. Post hoc comparisons were considered significant if  $p < .05$ . Pearson product-moment correlation coefficients assessed the relationship between behavioural and AEP thresholds for each frequency. Results of the correlation analyses were considered significant if  $p < .01$ .

## Results

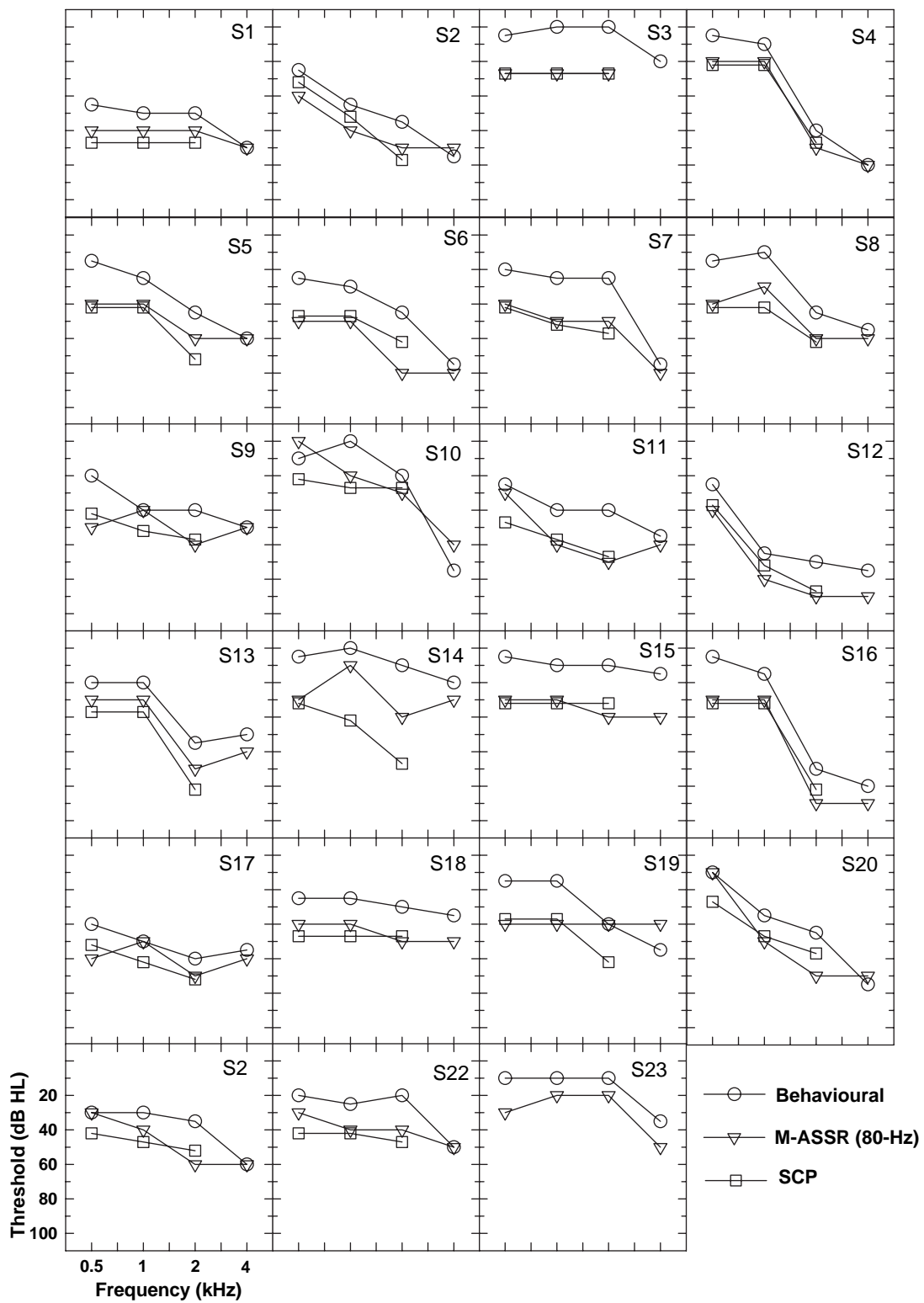
### Estimation of Behavioural Pure-Tone Thresholds

Figures 1 and 2 depict behavioural and multiple ASSR thresholds at 0.50, 1.0, 2.0, and 4.0 kHz, as well as SCP thresholds at 0.5, 1.0, and 2.0 kHz, for each subject in the 80 Hz and 40 Hz groups, respectively. Behavioural and AEP thresholds, as well as difference scores (AEP minus behavioural threshold), for each AEP at each frequency, and correlation coefficients are listed in Table 1. Table 2 presents the percentage of subjects where AEP thresholds were within 10 and 20 dB of behavioural pure-tone thresholds.

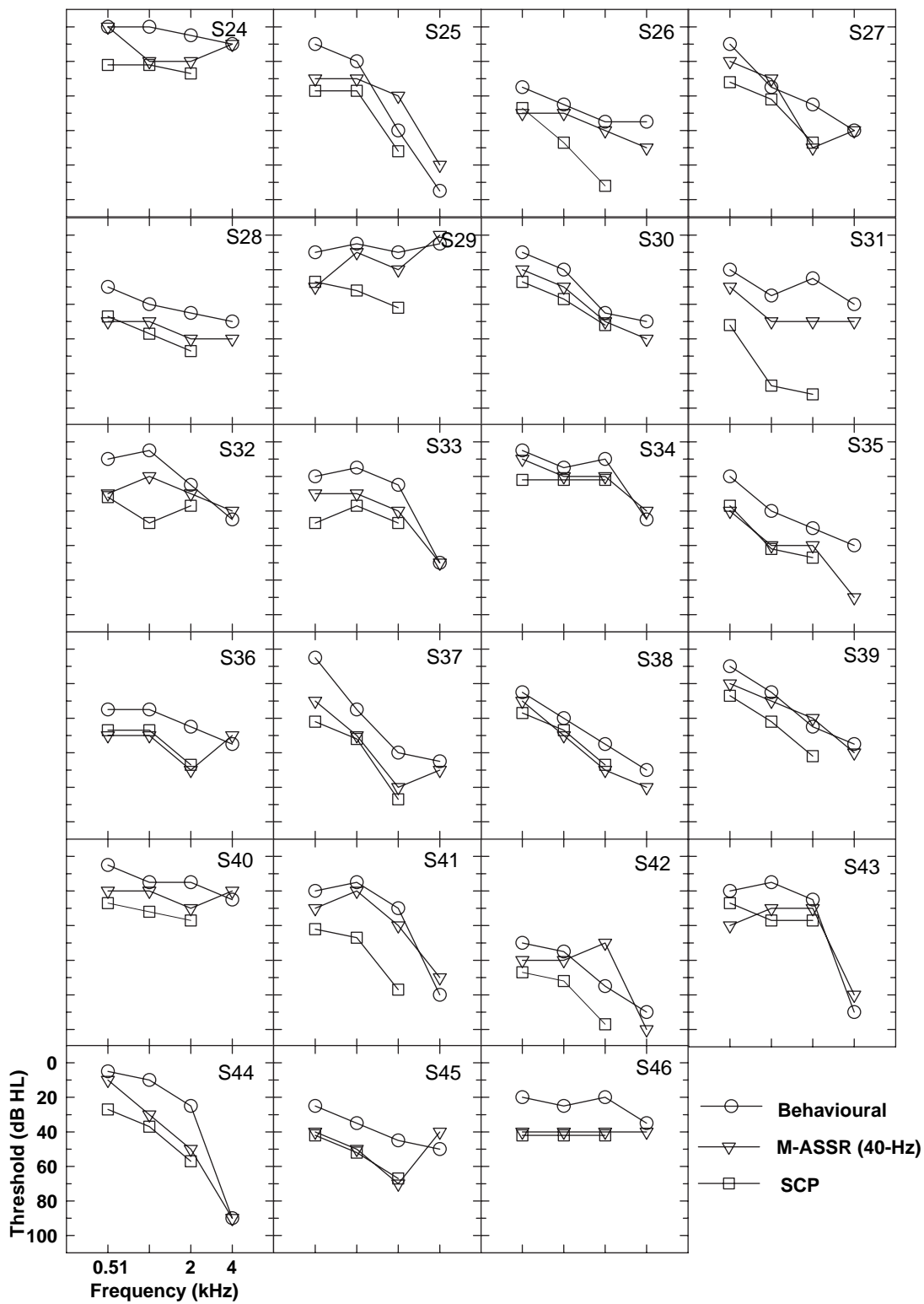
### 80 HZ VERSUS 40 HZ MULTIPLE ASSR

The 8 and 4 Hz ASSR were first analyzed separately from the SCP results because 4 kHz thresholds were not obtained in the SCP testing. Figures 1 and 2 illustrate that the 80 Hz and the 40 Hz multiple ASSRs are accurate predictors of behavioural thresholds for all frequencies, as well as providing good estimates of the degree and configuration of the behavioural pure-tone audiogram. Table 2 indicates that, at 0.5 kHz, far more subjects showed 40 Hz multiple ASSR thresholds within 20dB of behavioural thresholds compared to the 80 Hz multiple ASSR (96% versus 61%). The number of subjects showing ASSR thresholds within 20 dB of behavioural thresholds is similar between the two groups at 1, 2, and 4 kHz.

Table 1 indicates that the difference scores for the 40 Hz multiple ASSR are noticeably smaller (i.e. closer to behavioural threshold) than the 80 Hz multiple ASSR, with a very small difference score at 4 kHz. Two-way repeated measures ANOVA revealed significantly smaller ASSR-minus-behavioural-thresh-



**Figure 1.** Behavioural and 80 Hz multiple ASSR thresholds for 0.50, 1.0, 2.0, and 4.0 kHz and SCP thresholds for 0.5, 1.0, and 2.0 kHz plotted for each subject. Subject identifiers are in the top right-hand corner of each graph.



**Figure 2.** Behavioural and 40 Hz multiple ASSR thresholds for 0.50, 1.0, 2.0, and 4.0 kHz and SCP thresholds for 0.5, 1.0, and 2.0 kHz plotted for each subject. Subject identifiers are in the top right-hand corner of each graph.

**Table 1.** Mean and standard deviation for thresholds, difference scores, and correlation coefficients

<i>Test</i>	<i>(Carrier) Frequency</i>		<i>Behavioural Thresholds</i>		<i>AEP Thresholds</i>		<i>r</i>
	<i>(kHz)</i>	<i>n</i>	<i>(dB HL)</i>	<i>(dB HL)</i>	<i>Difference</i>		
80 Hz	0.5 kHz	23	18.3 ± 11.0	35.2 ± 13.7	17.0 ± 10.7	.65	
	1.0 kHz	23	24.8 ± 17.7	40.0 ± 16.2	15.2 ± 7.3	.91	
	2.0 kHz	23	38.3 ± 19.8	57.3 ± 18.8	19.1 ± 8.8	.90	
	4.0 kHz	23	56.3 ± 20.0	60.8 ± 16.2	4.4 ± 9.9	.87	
40 Hz	0.5 kHz	23	17.4 ± 12.1	30.8 ± 13.0	13.5 ± 6.5	.70	
	1.0 kHz	23	25.0 ± 14.5	36.1 ± 15.0	11.1 ± 5.8	.92	
	2.0 kHz	23	36.5 ± 18.7	47.8 ± 18.6	11.7 ± 13.7	.73	
	4.0 kHz	23	57.0 ± 24.2	57.4 ± 25.3	0.4 ± 9.4	.93	
SCP	0.5 kHz	45	18.0 ± 11.6	37.8 ± 10.9	19.8 ± 6.3	.81	
	1.0 kHz	45	25.2 ± 16.0	45.6 ± 14.1	20.3 ± 9.1	.82	
	2.0 kHz	45	38.0 ± 18.8	60.2 ± 18.9	22.2 ± 11.9	.80	

old difference scores for the 40 Hz group compared to the 80 Hz group [Group main effect:  $F=8.89$ ,  $df=1$ ,  $44$ ,  $p=.004$ ]. In addition, there was a significant effect of frequency [FREQ main effect:  $F=23.8$ ,  $df=3$ ,  $132$ ,  $p.001$ ]. For both ASSR groups, difference scores were smaller (better) at 4 kHz ( $p < .001$ ). There were no other significant effects.

#### MULTIPLE ASSR VERSUS SCP

Results in Figures 1 and 2 indicate that the SCP predicts the degree and configuration of the behavioural pure-tone threshold reasonably accurately. However, in no case does it appear to be better overall than the ASSR, and in some cases, it appears to be worse than the ASSR. Three-way repeated measures ANOVA compared estimation of behavioural pure-tone thresholds for all three AEPs at 0.5, 1.0, and 2.0 kHz. The ANOVA indicated a significant auditory evoked potential test (AEPTEST) main effect, with multiple ASSR difference scores smaller than SCP scores [ $F=31.4$ ,  $df=1$ ,  $43$ ,  $p=.001$ ]. However, there was a significant interaction, with lower scores for the 40 Hz multiple ASSR [AEPTEST x GROUP interaction:  $F=8.31$ ,  $df=1$ ,  $43$ ,  $p=.006$ ], and no difference between the 80 Hz multiple ASSR and the SCP difference scores [post hoc testing ( $p=.267$ )].

#### Correlation Coefficients

The correlation coefficients ( $r$ ) for pure-tone behavioural thresholds compared to ASSR or SCP thresholds are listed in Table 1. Figure 3 shows scatterplots representing the linear regression analysis comparing AEP (ASSR and SCP) thresholds with behavioural pure-tone thresholds for all subjects ( $n=23$  and  $45$  for ASSR and SCP tests, respectively) at 0.50, 1.0, 2.0, and 4.0 kHz for the ASSR, and at 0.5, 1.0, and 2.0 kHz for the SCP.

Figure 3 also shows the regression equations, sample size ( $n$ ), and correlation coefficients.

#### 80 HZ VERSUS 40 HZ MULTIPLE ASSR

Correlation coefficients reveal close relationships between behavioural and ASSR thresholds ( $r=.65-.93$ ) for all carrier frequencies. The lowest correlation coefficients were found for 0.5 kHz ( $r=.65$  and  $.70$  for 80 Hz and 40 Hz multiple ASSR, respectively). Pooled across all carrier frequencies, correlation coefficients were high and very similar for both the 80 Hz and 40 Hz multiple ASSRs ( $r=.88$  and  $.89$  for 80 Hz and 40 Hz multiple ASSRs, respectively).

#### MULTIPLE ASSR VERSUS SCP

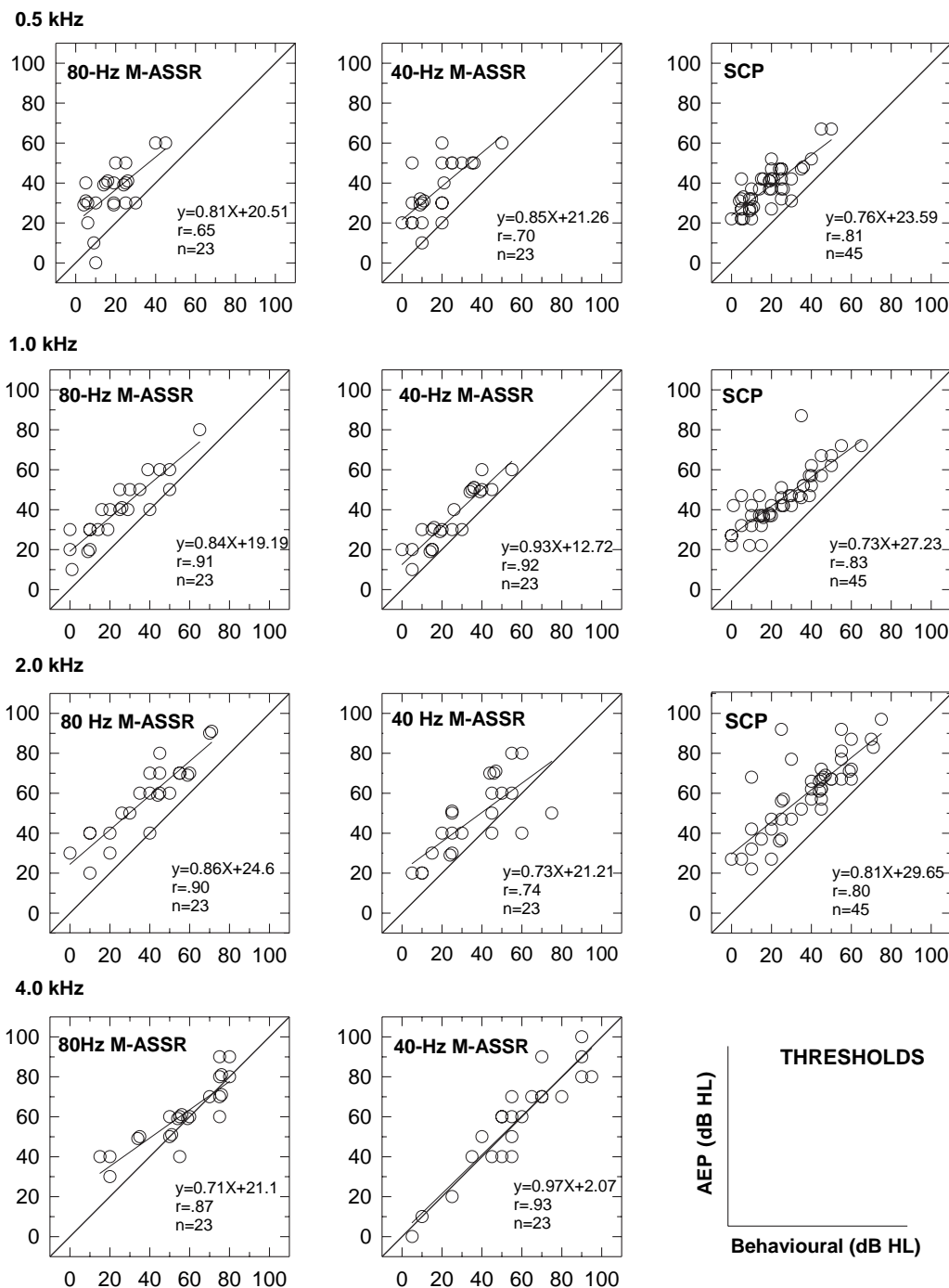
As shown in Table 1 and Figure 3, a higher correlation between SCP and behavioural threshold was found at 0.5 kHz than for either the 80 Hz or the 40 Hz multiple ASSR ( $r=.81$ ,  $.65$ , and  $.70$  for SCP, 80 Hz, and 40 Hz multiple ASSR, respectively). However, pooled across frequency, correlation coefficients between behavioural and AEP thresholds were nearly identical for ASSR and the SCP for subjects in both groups ( $r=.88$  and  $.89$  for 80 Hz and SCP, respectively; and  $r=.86$  and  $.84$  for 40 Hz and SCP, respectively).

#### AEP Recording Times

The recording times were estimated based upon collection of thresholds for four frequencies (one ear). The mean time required to estimate four thresholds for one ear is shown in Table 3. Table 4 indicates the percentage of subjects where time to estimate threshold took 60, 45, 30, and 15 minutes for four frequencies. Both tables indicate that SCP took the least time,

**Table 2.** Percentage of subjects, where AEP thresholds are within 10 or 20 dB HL of behavioural pure-tone thresholds

<i>Test</i>	<i>n</i>	<i>Difference (dB)</i>	<i>Frequency (kHz)</i>			
			<i>0.5</i>	<i>1.0</i>	<i>2.0</i>	<i>4.0</i>
80 Hz	23	≤10	26%	35%	26%	70%
		≤20	61%	87%	65%	97%
40 Hz	23	≤10	49%	52%	39%	78%
		≤20	96%	87%	65%	96%
SCP	45	≤10	2%	2%	2%	
		≤20	27%	29%	17%	



**Figure 3.** Scatter plots showing behavioural and AEP (multiple ASSR and SCP) thresholds. Linear regression equations, sample sizes ( $n$ ) and correlation coefficients ( $r$ ) are given in the lower right hand corner of the graphs. Overlapping data have been adjusted by  $\pm 1$  dB in both directions to resolve all points in the plots. The regression equation is as follows:  $y = mX + b$ , where  $y$  is the AEP threshold (in dB HL),  $X$  is the pure-tone behavioural threshold (in dB HL),  $m$  is the slope of the regression, and  $b$  is the y-intercept.

followed by the 40 Hz multiple ASSR, and then the 80 Hz multiple ASSR. The mean time of the SCP is almost six minutes faster than the mean time of the 40 Hz multiple ASSR, and 21 minutes faster than the mean time of the 80 Hz multiple ASSR. Table 3 shows that the mean time to estimate threshold for the 40 Hz multiple ASSR is over fifteen minutes faster compared to

the 80 Hz multiple ASSR (21 versus 36 minutes). Table 4 shows that over half of the 80 Hz group required more than 30 minutes to obtain thresholds, compared to only 11% of the 40 Hz group. SCP thresholds for all subjects were obtained under 30 minutes. Repeated measures ANOVA (and Neuman-Keuls post-hoc analyses) revealed that the times required to complete the SCP

**Table 3.** Mean, standard deviation, and median estimated time to obtain four frequencies in one ear

Test	n	Time (Minutes)		
		M	SD	Median
80 Hz	23	36.0	18.5	32.6
40 Hz	23	20.6	9.5	18.5
SCP	45	14.9	1.0	14.9

and the 40 Hz multiple ASSR were both significantly shorter than the 80 Hz multiple ASSR (AEPTEST  $\times$  GROUP interaction:  $F=12.4$ ;  $df=1, 43$ ;  $p=.001$  and post-hoc analysis  $p<.001$ ). There was a trend for SCP testing to be faster than the 40 Hz multiple ASSR, but this did not reach significance (Neuman-Keuls  $p=.085-.144$ ). As would be expected, there was no difference in the estimated time for SCP threshold estimation between the two groups ( $p=.86$ ).

### Discussion

The present study indicates that the 80 Hz and 40 Hz multiple ASSR, as well as the SCP, provide reasonable estimates of behavioural pure-tone thresholds and accurately predict the degree and the configuration of the hearing loss. Pooled across frequency, correlations between behavioural and AEP thresholds were nearly identical across the three AEP tests. However, AEP minus behavioural difference scores were best for the 40 Hz multiple ASSR, followed by the 80 Hz multiple ASSR and SCP. Time required to obtain a four-frequency audiogram for one ear was fastest for the SCP, followed by the 40 Hz multiple ASSR, and then the 80 Hz multiple ASSR.

#### Threshold Estimation: 80 Hz Multiple ASSR

In the present study, 80 Hz multiple ASSR threshold difference scores were on average, 4 to 17 dB, with multiple ASSR scores being higher than the behavioural thresholds. There have been several studies published regarding prediction of behavioural thresholds with 70–110 Hz ASSR (Aoyagi et al, 1994, 1999; Dimitrijevic et al, 2002; Herdman & Stapells, 2001, 2003, Lins et al, 1996; Perez-Abalo et al, 2001; Picton et al, 1998; Rance et al, 1995; Rance & Rickards, 2002). This research, including the present study, indicates that the ASSR using a MF of 70–110 Hz can accurately predict behavioural pure-tone thresholds. One exception is the study by Aoyagi et al (1994) which reports significantly elevated ASSR thresholds, large difference scores, and large standard deviations of  $39 \pm 15$ ,  $38 \pm 14$ ,  $35 \pm 15$  and  $20 \pm 14$  dB (for comparison to the present study, the Aoyagi data were converted to dB HL) for 0.50, 1.0, 2.0, and 4.0 kHz,

**Table 4.** Estimated time for four pure-tone thresholds: Percentage of subjects where threshold estimation was within 60, 45, 30, and 15 minutes

Test	n	Time (Minutes)			
		$\leq 60$	$\leq 45$	$\leq 30$	$\leq 15$
80 Hz	23	91%	74%	43%	13%
40 Hz	23	100%	100%	89%	43%
SCP	45	100%	100%	100%	56%

respectively, for twenty normal-hearing subjects. Picton et al (2003) speculated that the elevated thresholds might have been due to inadequate averaging time to detect responses close to threshold. In contrast, other researchers indicate remarkably close ASSR compared to behavioural thresholds (Rance & Rickards, 2002). These three retrospective studies examined the relationship between the ASSR thresholds determined in infancy and the subsequently obtained behavioural thresholds of over 100 subjects. These studies found very small difference scores of 11, 13, 8, and 7 dB for 0.50, 1.0, 2.0, and 4.0 kHz, respectively, for hearing-impaired subjects. One possible explanation for their small difference scores is the use of subjects with primarily severe or profound sensorineural hearing loss. These smaller difference scores are possibly due to subjects with sensorineural hearing loss having poorer temporal integration (Stapells et al, 1990).

Herdman & Stapells (2003) carried out a meta-analysis of studies of 70–110 Hz multiple ASSR thresholds. The meta-analysis indicated mean difference scores of 15, 15, 12, and 8 dB for 0.50, 1.0, 2.0, and 4.0 kHz respectively, similar to those of the present study. The meta-analysis indicated a significantly poorer accuracy of ASSR at 0.5 kHz compared to other frequencies. The present study did not show this same frequency effect for difference scores.

The present study indicated ASSR thresholds at 4 kHz are significantly closer to behavioural thresholds than any other carrier frequency. Although this is not a general finding in the literature, Herdman and Stapells (2003) looked at multiple ASSR specifically in steeply sloping losses and found that the difference score for 4 kHz was significantly smaller than those for 0.5, 1.0, and 2.0 kHz. This is similar to ABR findings in which the difference scores for 4 kHz are also significantly smaller than for other frequencies and may be due in part to the greater hearing loss at 4 kHz (Stapells, 2000b; Stapells et al, 1995).

The present study indicates good correlations between behavioural and 80 Hz ASSR. The correlations found in this study are consistent with others in the literature (Aoyagi et al, 1999; Herdman & Stapells, 2003, Lins et al, 1996; Perez-Abalo et al, 2001; Picton et al, 1998) but notably poorer than Rance & Rickards (2002) and better than Picton et al (1998). A possible explanation for the very high correlations presented by Rance and Rickards (2002) is their use of predicted behavioural thresholds extrapolated from the ASSR thresholds using regression equations, rather than the actual ASSR thresholds. Picton et al (1998) poor correlations may be related to their use of sound-field presentation of multiple-stimuli through the subjects' hearing aids.

The present study found the poorest 80 Hz ASSR correlation at 0.5 kHz ( $r=.65$ ). The meta-analysis of Herdman and Stapells (2003) revealed a significantly lower sensitivity of ASSR at 0.5 kHz. Other literature has raised concern regarding the sensitivity of a 80 Hz multiple ASSR at 0.5 kHz (Lins et al, 1996; Perez-Abalo et al, 2001). Lins et al (1996) indicated that for normal-hearing subjects, ASSR thresholds for 0.5 kHz were significantly elevated compared to thresholds at 1, 2, and 4 kHz. For the present study, 32 out of the 40 subjects (80%) had normal hearing at 0.5 kHz. The restriction of range of behavioural thresholds at 0.5 kHz is one possible reason for the poorer correlation at 0.5 kHz. Nevertheless, the poorer sensitivity of 80 Hz ASSR at 0.5 kHz, especially for normal-hearing subjects, is

of concern. This is especially true of the WCB clinical population with occupational noise-induced hearing loss. Occupational noise-induced hearing loss is characterized by normal low-frequency hearing thresholds. However, any non-organic overlay will be greatest in the low frequencies and decreased in the higher frequencies. This result often occurs due to recruitment when organic high-frequency hearing loss is also present (Coles & Mason, 1984). Therefore, a sensitive, objective measure at 0.5 kHz is desirable in this population.

#### *Threshold Estimation: 40 Hz Multiple ASSR*

The 40 Hz multiple ASSR threshold difference scores were on average 0 to 14 dB, with multiple ASSR scores being higher than the behavioural thresholds. As with 80 Hz multiple ASSR, there was no significant effect of frequency for 0.5, 1.0, and 2.0 kHz. However, the multiple ASSR threshold at 4 kHz was significantly closer to behavioural threshold than at any other carrier frequency.

To date, there has been no published study of the 40 Hz multiple ASSR for threshold estimation in adults. Previous studies of the single-stimulus 40 Hz ASSR indicate that the response can be recorded very close to behavioural pure-tone responses (for review, see Picton et al, 2003). Most studies using 40 Hz ASSR, including the present report, indicate ASSR thresholds within 10 to 20 dB of behavioural results.

The present study indicates that the 40 Hz multiple ASSR thresholds are significantly closer to behavioural results compared to the 80 Hz multiple ASSR. The 40 Hz multiple ASSR threshold difference scores are similar to other studies involving single stimuli. The finding of the ASSR threshold being significantly closer to behavioural threshold at 4 kHz is somewhat surprising given that the 40 Hz response significantly decreases in amplitude with increasing carrier frequency (Galambos et al, 1981; Picton, Skinner et al, 1987; Stapells et al, 1984). However, near threshold, amplitudes may not differ across frequency, although this was not assessed in the present study.

The results indicate that for threshold estimation in adults, the 40 Hz multiple ASSR is a better tool than the 80 Hz multiple ASSR. The 40 Hz multiple ASSR was also significantly closer to behavioural pure-tone thresholds than the SCP, even though a 5 dB step-size was used for the SCP.<sup>3</sup> Based upon accuracy alone, the 40 Hz multiple ASSR would be the method of choice for threshold estimation in adults with normal hearing and sensorineural hearing losses. However, time to obtain AEP thresholds is also a consideration.

#### *Threshold Estimation: SCP*

The SCP threshold difference scores were 20–22 dB. The SCP results showed good correlations for all frequencies; the correlation at 0.5 kHz is slightly better for SCP compared to ASSR. Results were similar to the 80 Hz multiple ASSR, but not as close to pure-tone behavioural thresholds as the 40 Hz multiple ASSR. The present study showed larger difference scores than Tsui et al (2002), who reported difference scores of

–2, –1 and –4 dB HL for 1, 2, and 3 kHz, respectively. There was no significant effect of frequency for 0.5, 1.0, and 2.0 kHz. This is consistent with other research that indicates the SCP is an appropriate tool for threshold estimation in passively cooperative adults (Adelman & Van Maanen, 2001; Alberti et al, 1987; Bonvier, 2002; Coles & Mason, 1984; Tsui et al, 2002). For this study, all stimuli (behavioural pure-tone stimuli, ASSR stimuli, SCP tonal stimuli) were specified in dB HL. Some studies use normal-hearing level (nHL) calibrations for SCP stimuli. SCP difference scores would have been approximately 9 dB smaller if nHL calibrations had been employed.

Results from this study confirm that the SCP is an accurate method for threshold estimation in a passively or actively alert adult population. However, the accuracy of SCP threshold estimation is dependent upon the skill and experience of the tester. As is the case with identification of other transient AEP waveforms, training and experience in SCP waveform identification influences estimates of threshold. One advantage of the multiple ASSR over the SCP is the removal of subjectivity of identification of waveforms.

#### *Estimated Recording Time Required to Obtain Four Thresholds*

Recording time (estimated from the number of sweeps) was under 60 minutes for 91% of the subjects in the 80 Hz multiple ASSR group, with a mean of 36 minutes. This is shorter than that of Herdman and Stapells (2003), who found a mean recording time of 47 minutes, but longer than that of Perez-Abalo et al (2001), who reported a mean recording time of 21 minutes for all four frequencies. The mean recording time of the present study may be within practical limits for assessment of hearing thresholds. However, the longest recording times (median time of over 50 minutes) might be impractical in a clinical setting. Of the three AEPs used in this study, the 80 Hz multiple ASSR took the longest to estimate behavioural thresholds. Importantly, 80 Hz multiple ASSR testing had to be abandoned more often than the 40 Hz multiple ASSR. Out of a total of 23 rejected subjects, twenty were from the 80 Hz multiple ASSR group. The large number of rejected subjects for the 80 Hz relative to the 40 Hz multiple ASSR group was related to background EEG noise of the subject and the noise criterion required for threshold identification of the ASSR. Excessive background EEG noise significantly extended the length of the 80 Hz ASSR test.

Recording time for the 40 Hz multiple ASSR estimated from the number of sweeps was under 45 minutes for all test subjects, with a mean recording time of 21 minutes. The 40 Hz multiple ASSR is therefore significantly faster than the 80 Hz multiple ASSR. Even the longest recording time of 42 minutes for the 40 Hz multiple ASSR would be within practical limits for threshold estimation. This finding has implications for the use of multiple ASSR with adult populations. The time savings alone would make evaluation by 40 Hz preferable over the 80 Hz multiple ASSR. As the results also indicated that 40 Hz multiple ASSR is significantly closer to behavioural threshold than 80 Hz multiple ASSR, it would appear to be the ASSR method of choice for threshold estimation for the adult population.

Estimated recording time for the SCP was under 30 minutes for all test subjects, with a mean recording time of fifteen minutes. Because recording time was calculated solely on sweep

<sup>3</sup>If a 10 dB step size had been utilized for the SCP, the mean difference scores would have changed no more than 1 dB (larger), with a 1–2 dB larger standard deviation. This was estimated by alternately adding or subtracting 5 dB to each SCP threshold that was not at a 10 dB step. This small change is similar to that reported by Luts and Wouters (2004).

times of each AEP for three frequencies, the time estimated to obtain thresholds for four frequencies (one ear) might be artificially advantageous to the SCP. Where the SCP requires additional time to change stimulus frequencies and to manipulate and identify waveforms etc. (approximately 15–20% additional time), the multiple ASSR has very little time involved other than the collection of sweeps.

Threshold estimation using the SCP is significantly faster than the 80 Hz multiple ASSR. There was a non-significant trend for the SCP to be faster than the 40 Hz multiple ASSR. However, the SCP might not necessarily be faster when thresholds for both ears are required. Obtaining results for both ears using the SCP requires approximately twice the amount of time compared to one ear. In contrast, the 40 Hz multiple ASSR theoretically might not require greater time because both ears can be tested simultaneously. However, any decrease in 40 Hz multiple ASSR amplitude when both ears are stimulated would reduce its efficiency, perhaps requiring 50% more time to test both ears (compared to one ear) (John, et al, 1998). John and colleagues reported a 33% decrease in amplitude going from four 75 dB SPL stimuli (four in one ear) to eight stimuli (four in each ear) (John, et al, 1998). However, pilot data from our lab indicate little or no amplitude reduction for near-threshold multiple stimuli. All considered, the recording time required to test both ears (four frequencies) would be approximately 30 minutes for the SCP and 21–31 minutes for the 40 Hz multiple ASSR.<sup>4</sup>

#### *Stimulus Considerations*

The modulation rates for the 40 Hz multiple ASSR used in this study had 3 Hz separation between the modulation frequencies. Modulation rates for the circa 40 Hz multiple ASSR were chosen based upon limited research on this issue (John et al, 1998) and our pilot data. According to the present study, use of the above modulation frequencies for 40 Hz multiple ASSR results in accurate estimates of behavioural pure-tone thresholds. Future research might determine even more optimal MF separations than those used in the present study.

#### *Recording Considerations*

As previously stated, the 80 Hz ASSR has advantages over the 40 Hz ASSR in that it is unaffected by sleep; in fact the detection of its presence maybe enhanced in sleep (Levi et al, 1993). However, a sleep state might be difficult to obtain in adult subjects. Although the 40 Hz multiple ASSR is not appropriate for infants or sleeping subjects, subject state should not be a factor preventing its use in adults. Ensuring an optimum physiologic state (i.e. keeping the subject alert and quiet) of the subject is usually readily achieved. We found that keeping the client passively or actively alert for the estimation of four pure-tone thresholds using the 40 Hz multiple ASSR, typically 21 minutes, was not problematic. As indicated above, some adults might be too noisy to test using the 80 Hz multiple ASSR.

The two main pitfalls to the recording and analysis of the SCP are management of the state of the subject (i.e. ensuring the subject awake and alert and not drowsy) and the skill and

<sup>4</sup>Use of the 5 dB step size was estimated to require approximately two to three minutes extra testing for the SCP. However, this is offset by an equal amount by the 15–20% extra time required for the SCP to change frequencies and ears, and to manipulate waveforms, etc. The estimate for the SCP for two ears is thus approximately 30 minutes (2 × 14.9 minutes).

experience of the clinician. Controlling the subject state, the EEG, and the alpha rhythm is an integral part of obtaining the SCP (Hyde, 1994; Stapells, 2002). However, as noted above, we have not found this to be problematic in our clinic. As with any AEP, there is inter-subject variation in waveforms, and the clinician must have the skill and experience to identify SCP waveforms.

## **Conclusions**

The present study confirms other research showing that SCPs, and 40 and 80 Hz multiple ASSRs can accurately predict behavioural audiograms in adult subjects with normal hearing and sensorineural hearing impairments. This study indicates that the 40 Hz multiple ASSR provides an estimation of behavioural results significantly better than the 80 Hz multiple ASSR and the SCP (based on difference scores). Correlations are similar for all three AEP measures, thus, thresholds predicted using regression formulae might be similarly accurate for all three tests. Some adults might be too noisy to complete 80 Hz multiple ASSR testing, especially compared to 40 Hz multiple ASSR or SCP testing. The SCP took less time to estimate threshold than either multiple ASSR method, although not significantly less than the 40 Hz multiple ASSR. Although SCP is a good choice for behavioural threshold estimation in adults, the training of clinicians in identifying SCP waveforms would likely be more time consuming than ASSR, where there is no subjective waveform identification required. In addition, the SCP must be recorded one stimulus frequency at a time and one ear at a time. Thus, this time-saving advantage of the SCP would not hold true for dichotic testing. In other words, under similar conditions to the present study, 40 Hz multiple ASSR might be faster than the SCP for threshold estimation for eight frequencies (four frequencies per ear). Under optimal circumstances (i.e. clinical protocols for the SCP are well established and clinicians are well trained and experienced), the SCP is an accurate and timely means of threshold estimation for adults. However, when one considers the objectivity and accuracy of response determination of the ASSR, the difficulty in obtaining training and experience with SCP testing, and the potential need for more than three frequencies for each ear, the 40 Hz multiple ASSR is likely the method of choice for AEP threshold estimation in adults.

## **Acknowledgements**

Grants from the Canadian Institutes of Health Research supported this research. We sincerely thank the Workers' Compensation Board of British Columbia for their generous contribution to this research.

## **References**

- Adelman, S. & Van Maanen, A. July 2001. Use of SVP for threshold estimation in WCB claimants. Poster presented at the 17th meeting of the International Evoked Response Audiometry Study Group Symposium, Vancouver, Canada.
- Alberti, P., Hyde, M. & Riko, K. 1987. Exaggerated hearing loss in compensation claimants. *J Otolaryngol*, 16, 362–366.
- Aoyagi, M., Kiren, T., Furuse, H., Fuse, T., Suzuki, Y., et al. 1994. Pure-tone threshold prediction by 80 Hz amplitude-modulation following response. *Acta Otolaryngol Suppl*, 511, 7–14.

- Aoyagi, M., Kiren, T., Kim, Y., Suzuki, Y., Fuse, T., et al. 1993. Optimal modulation frequency for amplitude-modulation following response in young children during sleep. *Hear Res*, 65, 253–261.
- Aoyagi, M., Suzuki, Y., Yokota, M., Furuse, H., Watanabe, T., et al. 1999. Reliability of 80 Hz amplitude modulation-following response detected by phase coherence. *Audiol Neurootol*, 4, 28–37.
- Bonvier, R. 2002. Slow auditory evoked potentials: The end of malingering in audiology. *Int Tinnitus J*, 8, 58–61.
- Coles, R. R. A. & Mason, S. M. 1984. The results of cortical electric response audiometry in medico-legal investigations. *Br J Audiol*, 18, 71–78.
- Dimitrijevic, A., John, M. S., Van Roon, P., Purcell, D. W., Adamonis, J., et al. 2002. Estimating the audiogram using the multiple auditory steady-state responses. *J Am Acad Audiol*, 13, 205–224.
- Galambos, R., Makeig, S. & Talmachoff, P. J. 1981. A 40 Hz auditory potential recorded from the human scalp. *Proc Natl Acad Sci USA*, 78, 2643–2647.
- Herdman, A. H. & Stapells, D. R. 2001. Thresholds determined using the monotic and dichotic multiple auditory steady-state response technique in normal-hearing subjects. *Scand Audiol*, 30, 41–49.
- Herdman, A. H. & Stapells, D. R. 2003. Auditory steady-state response thresholds of adults with sensorineural hearing impairments. *Int J Audiol*, 42, 237–248.
- Hyde, M. L. 1994. The slow vertex potential: Properties and clinical applications. In J. T. Jacobson (ed.), *Principles and Applications in Auditory Evoked Potentials*. Boston: Allyn and Bacon, pp. 179–218.
- Jerger, J., Chmiel, R., Frost, J. D. & Coker, N. 1986. Effect of sleep on the auditory steady-state potential. *Ear Hear*, 7, 240–245.
- John, M. S., Dimitrijevic, A. & Picton, T. W. 2002. Auditory steady-state responses to exponential modulation envelopes. *Ear Hear*, 23, 106–117.
- John, M. S., Lins, O., Boucher, B. & Picton, T. W. 1998. Multiple auditory steady-state responses (MASTER): Stimulus and recording parameters. *Audiology*, 37, 59–82.
- John, M. S. & Picton, T. W. 2000. MASTER: a windows program for recording multiple auditory steady state responses. *Comput Methods Programs Biomed*, 61, 125–150.
- John, M. S., Purcell, D. W., Dimitrijevic, A. & Picton, T. W. 2002. Advantages and caveats when recording steady-state responses to multiple simultaneous stimuli. *J Am Acad Audiol*, 13, 246–259.
- Levi, E. C., Folsom, R. C. & Dobie, R. A. 1993. Amplitude-modulation following response (AMFR): Effects of modulation rate, carrier frequency, age, and state. *Hear Res*, 68, 42–52.
- Linden, R. D., Campbell, K. B., Hamel, G. & Picton, T. W. 1985. Human auditory steady-state potentials during sleep. *Ear Hear*, 6, 167–174.
- Lins, O. G. & Picton, T. W. 1995. Auditory steady-state responses to multiple simultaneous stimuli. *Electroencephalogr Clin Neurophysiol*, 96, 420–432.
- Lins, O. G., Picton, T. W., Boucher, B. L., Durieux-Smith, A., Champagne, S. C., et al. 1996. Frequency-specific audiometry using steady-state responses. *Ear Hear*, 17, 81–96.
- Luts, H. & Wouters, J. 2004. Hearing assessment by recording multiple auditory steady-state responses: the influence of test duration. *Int J Audiol*, 43, 471–478.
- Oates, P. & Stapells, D. R. 1998. Auditory brainstem response estimates of the audiogram: current status. *Semin Hear*, 19, 61–84.
- Pethe, J., von Specht, H., Muhler, R. & Hocke, T. 2001. Amplitude modulation following responses in awake and sleeping humans: A comparison for 40 Hz and 80 Hz modulation frequency. *Scand Audiol Suppl*, 52, 152–155.
- Perez-Abalo, M., Savio, G., Torres, A., Martin, V., Rodríguez, E., et al. 2001. Steady state responses to multiple amplitude-modulated tones: an optimized method to test frequency-specific thresholds in hearing-impaired children and normal-hearing subjects. *Ear Hear*, 22, 200–211.
- Picton, T. W. 1991. Clinical usefulness of auditory evoked potentials: A critical evaluation. *J Speech-Lang Path Audiol*, 15, 3–16.
- Picton, T. W., Dimitrijevic, A. & John, M. S. 2002. Multiple auditory steady-state responses. *Ann Otol Rhinol Laryngol Suppl*, 111, 16–21.
- Picton, T. W., Dimitrijevic, A., Perez-Ablo, M., & Van Roon, P. (2005). Estimating audiometric thresholds using auditory steady-state responses. *J Am Acad Audiol*, 16, 140–156.
- Picton, T. W., Durieux-Smith, A., Champagne, S. C., Whittingham, J., Moran, et al. 1998. Objective evaluation of aided thresholds using auditory steady state responses. *J Am Acad Audiol*, 9, 315–331.
- Picton, T. W., John, M. S., Dimitrijevic, A. & Purcell, D. 2003. Human auditory steady-state responses. *Int J Audiol*, 42, 177–219.
- Picton, T. W., Skinner, C. R., Champagne, S. C., Kellet, A. J. C. & Maiste, A. C. 1987. Potentials evoked by the sinusoidal modulation of the amplitude or frequency of a tone. *J Acoust Soc Am*, 82, 165–178.
- Picton, T. W., Vajsar, J., Rodriguez, R. & Campbell, K. B. 1987. Reliability estimates for steady-state evoked potentials. *Electroencephalogr Clin Neurophysiol*, 68, 119–131.
- Plourde, G., Stapells, D. R. & Picton, T. W. 1991. The human auditory steady-state evoked potentials. *Acta Otolaryngol Suppl*, 491, 153–160.
- Rance, G., Rickards, F., Cohen, L., De Vidi, S. & Clark, G. 1995. The automated prediction of hearing thresholds in sleeping infants using auditory steady-state evoked potentials. *Ear Hear*, 16, 499–507.
- Rance, G. & Rickards, F. 2002. Prediction of hearing threshold in infants using auditory steady-state potentials. *J Am Acad Audiol*, 13, 236–245.
- Small, S. & Stapells, D. R. (2005). Multiple auditory steady-state responses to bone conduction stimuli in adults with normal hearing. *J Am Acad Audiol*, 16, 172–183.
- Stach, B. A., Jerger, J. F. & Penn, T. O. 1994. In J. T. Jacobson (ed.), *Principles and Applications in Auditory Evoked Potentials*. Boston: Allyn and Bacon, pp. 541–560.
- Stapells, D. R. 2000a. Frequency-specific evoked potential audiometry in infants. In R. C. Seewald (ed.), *A Sound Foundation Through Early Amplification*. Basel: Phonak AG, pp. 13–31.
- Stapells, D. R. 2000b. Threshold estimation by the tone-evoked auditory brainstem response: A literature meta-analysis. *J Speech-Lang Path Audiol*, 224, 74–83.
- Stapells, D. R. 2002. Cortical event-related potentials to auditory stimuli. In J. Katz (ed.), *Handbook of Clinical Audiology*. Baltimore: Lippincott, Williams & Wilkins, pp. 378–406.
- Stapells, D. R., Galambos, R., Costello, J. A. & Makeig, S. 1988. Inconsistency of auditory middle latency and steady-state responses in infants. *Electroencephalogr Clin Neurophysiol*, 71, 289–295.
- Stapells, D. R., Gravel, J. S. & Martin, B. A. 1995. Thresholds for auditory brain stem responses to tones in notched noise from infants and young children with normal-hearing or sensorineural hearing loss. *Ear Hear*, 16, 361–371.
- Stapells, D. R., Linden, D., Suffield, J. B., Hamel, G. & Picton, T. W. 1984. Human auditory steady-state potentials. *Ear Hear*, 5, 105–113.
- Stapells, D. R., Picton, T. W., Durieux-Smith, A., Edwards, C. & Moran, L. 1990. Thresholds for short-latency auditory-evoked potentials to tones in notched noise in normal-hearing and hearing-impaired subjects. *Audiology*, 29, 262–274.
- Suzuki, T. & Kobayashi, K. 1984. An evaluation of 0.040 kHz event-related potentials in young children. *Audiology*, 23, 599–604.
- Tsui, B., Wong, L. & Wong, E. 2002. Accuracy of the cortical evoked response audiometry in the identification of non-organic hearing loss. *Int J Audiol*, 41, 330–333.
- Vander Werff, K. R., Brown, C. J., Gienapp, B. A. & Schmidt Clay, K. M. 2002. Comparisons of auditory steady-state response and auditory brainstem response thresholds in children. *J Am Acad Audiol*, 13, 227–235.