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Prediction of Hearing Thresholds: Comparison of Cortical Evoked Response Audiometry and Auditory Steady State Response Audiometry Techniques

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Abstract

The present study evaluated how well auditory steady state response (ASSR) and tone burst cortical evoked response audiometry (CERA) thresholds predict behavioral thresholds in the same participants. A total of 63 ears were evaluated. For ASSR testing, 100% amplitude modulated and 10% frequency modulated tone stimuli at a modulation frequency of 40 Hz were used. Behavioral thresholds were closer to CERA thresholds than ASSR thresholds. ASSR and CERA thresholsd were closer to behavioral thresholds at higher than at lower frequencies. Although predictions based on CERA thresholds are slightly more accurate than ASSR threshold, the differences may not be clinically significant particularly when the degree of individual variations is considered. Prediction of hearing thresholds became more accurate when hearing loss increased. Due to variations in prediction across participants, a single correction factor cannot be used. Other factors must be considered in selecting whether to use CERA or ASSR in predicting behavioral thresholds.

Introduction

Cortical evoked response audiometry (CERA) has been used to objectively estimate hearing sensitivity in difficult-to-test adults and children (Tsui, Wong & Wong, 2002). Similarly, ASSR has been used for threshold estimation in adults (Hsu, Wu, & Liu, 2003), and the 80-Hz ASSR has also been used for threshold estimation in children (Con-Wesson, Dowell, Tomlin, Rance, & Ming, 2002). Both ASSR and CERA allow threshold estimation at specific frequencies, but questions remain as to whether one provides more accurate prediction than another.

CERA prediction of hearing threshold

CERA records scalp potentials using clicks, tone stimuli or speech stimuli. CERA responses are characterized by a negative (N1) peak and a positive (P2) peak, reflecting synchronous neural activation in the thalamic-cortical segment of the central auditory system (Naatanen & Picton, 1987). N1 occurs at approximately 100 ms and P2 at about 150 ms after the onset of stimulus (Prasher, Mula & Luxon, 1993; Hyde, 1997), and is used to evaluate hearing sensitivity (Prasher et al 1993; Hyde 1997; Tsui et al 2002).

Previous research has suggested that hearing thresholds can be accurately predicted using CERA. For example, Prasher et al (1993), Tsui et al (2002) and Hyde, Matsumoto, Alberti & Yao (1986) found that CERA could be used to predict pure-tone behavioral thresholds to within 10 dB in a group of compensation claimants with non-organic hearing loss. CERA thresholds have high correlations with pure-tone behavioral thresholds (Prasher et al 1993; Tsui et al 2002). Overall maximum discrepancies between the two measurements were about 15 dB at 500 Hz (Hyde et al, 1986), 10 dB at 1000 Hz (Prasher et al, 1993; Tsui et al, 2002), 10 dB at 2000 Hz (Tsui et al, 2002), and 10 dB at 4000 Hz (Prasher et al, 1993; Tsui et al, 2002).

ASSR prediction of hearing threshold

ASSR can also be used to predict hearing sensitivity in adults with non-organic hearing loss (Hsu et al, 2003), and in infants or children (Rance & Rickards, 2002). ASSR is recorded on the scalp as brain responses evoked by a continuous acoustic stimulus that is modulated periodically. The tone can be amplitude modulated (AM) and/or frequency modulated (FM). When stimulated, cochlear hair cells in the region that correspond to the carrier frequency are activated (Rance, Dowell, Rickards, Beer & Clark, 1998). As neural activity travels along the auditory pathways, responses occur at the modulation frequency. The presence of ASSR is determined using computer algorithms that often utilize Fast Fourier Transform (FFT) analysis to yield information on Phase Coherence (PC), Magnitude Square Coherence (MSC) or variance analysis (F-test). PC is related to the phase distribution of the electroencephalographic (EEG) signal activity, MSC is related to both amplitude and phase information while F-test usually is related to the power amplitude of the response (Cone-Wesson & Dowell et al, 2002).

It is unclear where exactly ASSR is generated. In general, the generation site and response of ASSR correspond to the carrier frequency and a specific modulation rate between 20 and 200 Hz. (Cone-Wesson & Dowell et al, 2002). Responses generated at a modulation frequency of 20 Hz or below appear to originate in late cortical structures associated with the primary auditory cortex while responses generated at a modulation frequency between 20 and 60 Hz are similar to middle latency responses (MLRs) from centers close to the auditory midbrain and primary auditory cortex (Chambers, Feth & Burns, 1986; Picton, Skinner, Champagne, Kellett & Maiste, 1987; Cohen, Rickards & Clark, 1991). Responses generated at a modulation frequency higher than 60 Hz seem to reflect brainstem processes (Cone-Wesson & Dowell et al, 2002). Rance and Briggs (2002), and Rance et al (1998) suggested that a modulation frequency above 70 Hz could be used to obtain reliable responses in sleeping infants and children. Cohen et al (1991) and Cone-Wesson and Dowell et al (2002) suggested that a modulation frequency of 40 Hz could be used to generate robust responses in awake adults.

ASSR and pure-tone behavioral thresholds are found to be within ±15 dB (Herdman & Stapells, 2003; Rance & Rickards, 2002); individual differences can be much larger (Rance, Rickards, Cohen, Devidi & Clark, 1995; Rance & Rickards, 2002; Rance & Briggs, 2002; Cone-Wesson, Rickards, Poulis, Parker, Tan et al, 2002; Rickards, Tan, Cohen, Wilson & Drew et al, 1995; Hsu et al, 2003). ASSR and pure-tone behavioral thresholds are significantly correlated (r = .86 to 0.95, $p < .01$) at the octave frequencies between 500 and 4000 Hz in infants and adults (Hsu, et al, 2003). The correlations increase with test frequency and the degree of hearing loss (Picton, John, Dimitrijevic & Purcell, 2003; Rance et al, 1995). The above results were obtained using single-stimulus ASSR. ASSR can also be obtained using multiple ASSR stimuli with multiple amplitude-modulation tones (77 to 105 Hz) at several test frequencies (e.g., 500, 1000, 2000 and 4000 Hz) that are simultaneously presented to one ear. Previous research has shown that results obtained with multiple ASSR stimuli at 500 to 4000 Hz are also significantly correlated with behavioral thresholds (r = .75 to .89, $p < .001$) in adults (Herdman and Stapells, 2003).

Aims of the study

Although past research has shown both CERA and ASSR predict pure-tone behavioral thresholds quite accurately, no study has evaluated how results obtained using these two measures compared to each other on the same individuals. The main purpose of the present study was to compare how well ASSR and CERA predict pure-tone behavioral thresholds in adults with normal hearing or sensorineural hearing loss. As the interpretation of CERA results is subjected to judgment of a clinician, it is important that the inter-tester reliability for CERA be established so that accurate comparisons between CERA and ASSR can be made. Therefore, judgments from two experienced clinicians were compared to yield the most accurate results. Inter-tester reliability was also evaluated.

Method

Participants

A total of 34 adults (15 males and 19 females) aged between 23 and 69 years (M = 45.6 years) participated in the study. They had normal hearing or mild to profound sensorineural hearing loss. Five ears with type B tympanograms were excluded, leaving a total of 63 ears for analysis. The 63 ears were divided into 3 hearing loss groups according to their pure-tone average thresholds calculated at 500, 1000 and 2000 Hz: normal hearing (-10 to 25 dB HL,19 ears), mild to moderately severe hearing loss (26 to 70 dB HL, 24 ears), and severe to profound hearing loss (> 71 dB HL, 20 ears).

Equipment

A Grason Stadler GSI 33 middle ear analyzer, calibrated according to manufacturer's specifications, was used for immittance audiometry. A Madsen OB 822 clinical audiometer calibrated according to ANSI S3.6-1996 standard was used for pure-tone audiometry. Pure-tone air-conduction stimuli were presented to the test ear via a set of TDH-50P headphones. The stimuli were calibrated using a Bruel and Kjaer 6-cc coupler. The B71 bone-conductor was calibrated using a Bruel and Kjaer artificial mastoid. The headphone and bone vibrator were calibrated in dB HL.

A Grason Stadler GSI Audera AEP testing system was used for ASSR and CERA testing so that the same set of electrodes was applied. For CERA testing, tone-burst stimuli calibrated in dB nHL were presented to the test ear via a set of TDH-39P headphones. For ASSR testing, 100% AM and 10% FM modulated tones were presented at a modulation frequency of 40 Hz to the test ear via the same set of TDH-39P headphones calibrated in dB HL. This modulation rate was chosen because it yields robust responses in hearing-impaired adults (Cohen et al, 1991; Cone-Wesson & Dowell et al, 2002). ASSR and CERA responses were measured with disposable Nikomed scalp electrodes placed on the vertex, the forehead, and both ear lobes. The ASSR/CERA equipment was calibrated according to ANSI S3.6-1996 standard using a Larson Davis 6cc-coupler.

Procedures

Otoscopic examination and immittance audiometry were conducted, followed by pure-tone audiometry, ASSR and CERA. Pure-tone air-conduction thresholds were measured at the octave frequencies between 250 and 8000 Hz using the standard Hughson-Westlake clinical procedure in 5 dB steps. Bone-conduction thresholds were measured at 500 Hz to 4000 Hz using the same procedure. Ears yielded type B tympanograms were excluded, leaving 63 ears for data analysis. None of the remaining 63 ears had air-bone gaps greater than 10 dB.

As CERA and ASSR results are influenced by arousal level and attentiveness to the test stimuli (Naatanen & Picton, 1987; Rance et al, 1995). A 10-minute break was given after CERA and before ASSR to minimize fatigue during ASSR testing. Participants were monitored throughout the session. Those who were falling asleep during CERA or ASSR testing were given other short breaks, followed by repeated measurements at the same level and only complete measurements were used for data analysis. Electrode impedances measured before and after CERA and ASSR, and after each break were less than 5 kΩ for all participants.

As there was no standard protocol for CERA testing, test parameters commonly used in other studies were employed (Prasher et al, 1993; Tsui et al, 2002). Alternating tone busts with repetition rate of 1.2 per second and rise/fall times of -50 ms and 163 ms were used as test stimuli. The filter bandwidth was set at 1 to 30 Hz and 32 sweeps were collected for each averaging to ensure good N1 waveform morphology. The rejection level was set at 10%. CERA thresholds were recorded on the 63 test ears using tone-burst stimuli at 500, 1000, 2000 and 4000 Hz presented in random order.

CERA test protocol in this study was designed to evaluate and ensure inter-tester and test-retest reliability. Therefore, responses were recorded at least twice at each intensity level to ensure repeatability of waveform. The waveform morphology of the second waveform should be comparable to the first waveform, and the latency of N1 between two waveforms should be within 10 ms. The initial stimuli level was set at 40 dB Sensation Level (SL) or the maximum output of the instrument at 120 dB nHL if the hearing loss exceeded 80 dB HL. This level should be sufficient to elicit an initial positive CERA response because previous research have shown that CERA and pure-tone behavioral thresholds differ by an average of 10 dB and no more than 30 dB (Hyde et al, 1986; Prasher et al, 1993; Tsui et al, 2002). An adaptive bracketing technique was used to determine the CERA thresholds. If a response was recorded at the initial test level, the stimulus intensity was reduced in 20 dB steps until no detectable waveform was observed. Stimulus level was then increased by 10 dB. The test then proceeded with a reduction in stimulus level by 5 dB following a positive response, or an increase by 5 dB following a negative response for the final trial. Using this procedure, CERA responses were obtained on all participants below the initial test level. Participants were instructed to relax and count the number of beeps presented to maintain their alertness. Participants were also instructed to avoid neck and mouth movement. EEG activity was monitored and if more than 10% of responses were rejected, the testing was stopped and participants were reinstructed to relax or if they seemed tired, they would be given a short break. Only recordings from a complete run were used in data analysis.

The presence of the N1-P2 complex was used as the detection criterion for CERA threshold interpretation (Prasher et al, 1993). In addition, changes in N1-P2 latencies between 80 and 150 ms were used to aid identification of responses. Thresholds were determined as the lowest stimulus level at which N1 was visually detected in the waveform. To evaluate and ensure inter-tester reliability, CERA thresholds were first determined by the first author during data collection. Results were then forwarded to two other audiologists with more than 10 years of experience using CERA in regular practice. The two audiologists were blinded to the participants' pure-tone thresholds and the test procedures in order to reduce bias. When the interpretations of the two audiologists differed, the average results were used.

ASSR thresholds were recorded on the 63 test ears at 500, 1000, 2000, and 4000 Hz using a random test order. Due to a lack of standard protocol for ASSR, default test parameters in the equipment were used for the present study. The tones were amplitude modulated at 100% and frequency modulated at 10% with a modulation rate of 40 Hz. This modulation rate was chosen because it may yield lower threshold in testing awake adults (Cone Wesson, Dowell et al., 2002). The lower modulation rate may allow the neurons to time-locke more precisely to the stimulus (Dimitrijevic et al., 2002). The filter bandwidth was 0.2 Hz to 10 k Hz. Samples of EEG activity were recorded and analyzed as the continuous modulated tone was presented. A maximum number of 64 sweeps were analyzed in each trial. The determination of a "phase-locked" response versus a "random" response is based on statistical analyses that are completed in real-time. Responses were detected automatically using a phase coherence detection criterion. A response is considered as phased-locked or present if within the 64 sweeps, the sampled EEG phase distributions are in phase (see Fig. 1 for an example). That is, the phase coherence value is close to 1.0 and there is a less than 3% chance that the response is due to noise alone. A phase coherence value close to 0 indicates that the sampled EEG phase distributions are in random or absence of response (see Fig. 1b for an example). A maximum of 64 sweeps were obtained. The measurement would halt before the 64 sweeps were completed if within these sweeps, a phase-locked response is detected. Otherwise, stimulation and data sampling would continue until after 64 EEG samples had been analyzed or when the above criterion could not be achieved after 64 sweeps, resulting in a radom response (see Fig. 1c for an example). Threshold was determined as the lowest stimulus level at which a phase-locked response is illicited. When a noisy response was obtained, the measurement was repeated at the same intensity level at identical frequency. In order to reduce EEG noise, participants were instructed to relax, close their eyes when signals were present and open their eyes only when there was no signal. Participants were also instructed to avoid neck and mouth movements. To reduce bias due to foreknowledge of hearing thresholds, a test protocol similar to the one used for CERA testing was adopted. That is, the initial test level was set at 40 dB SL, or the maximum output of the instrument at 120 dB HL if the hearing loss exceeded 80 dB HL. This level should be adequate in eliciting a response as past studies have shown that ASSR thresholds should be within 15 dB of pure-tone behavioral thresholds (Hsu et al, 2003; Herdman & Stapells, 2003). If a response was recorded at the initial test level, the stimulus intensity was reduced in 20 dB steps until no detectable waveform was observed. Stimulus level was then increased by 10 dB. The test then proceeded with a reduction in stimulus level by 5 dB HL following a positive response, or an increase by 5 dB following a negative response for the final trial. Using this procedure, ASSR responses were obtained on all participants below the initial test level.

Results

Data analyses were conducted using SPSS (version 10.0) on the 63 ears that met the selection criteria.

Real-time EEG recording on ASSR and CERA

In order to ensure that physiological noises had minimal effects on the recordings, real-time EEG recordings were monitored. During CERA testing, response rejection rate stayed very low and each sweep did not take more than 30 seconds to complete, suggesting low noise recordings. Among the 1088 ASSR complete recordings, only 7.6% of these recordings were considered noisy. These recordings were repeated at the same level to yield non-noisy responses for data analysis.

Inter-tester reliability for CERA testing

A total of 252 judgments (63 test ears x 4 test frequencies) on CERA results were made by each experienced audiologist. Among these judgments between the two audiologists, 218 (86.5%) were identical, 24 (9.5%) differed by 5 dB, and 10 (4.0%) were within 10 dB. For the 34 discrepant interpretations, the mean level was used as the final CERA threshold.

Discrepancy between ASSR and CERA thresholds and behavioral audiometric thresholds

A general linear model (GLM) analysis for repeated measures (with Bonferroni corrections) was conducted to evaluate whether there were significant differences in the results obtained at the four test frequencies using the three assessment procedures. Within-subjects effects were significant across test frequency $F(3) = 39.3$, $p < .001$, and test procedures, $F(2) = 107.4$, $p < .001$. No Significant interaction between test frequency and the type of assessment procedures was noted, $F(6) = .80$, $p > .05$. Post hoc tests also showed that results obtained using the three measures of hearing thresholds were significantly different ($p < .001$). Thresholds obtained at all frequencies were significantly different from each other ($p < .001$).

The mean difference between ASSR/CERA and behavioral thresholds at 500, 1000, 2000 and 4000 Hz for the three hearing categories are shown in Table 1. Mostly positive overall and individual group mean deviations indicated that mean ASSR and CERA thresholds were greater than mean behavioral thresholds (see Table 1). On average, CERA thresholds differed from behavioral thresholds by -1.8 to 7.9 dB, compared to 4.3 to 13.7 dB between ASSR and behavioral thresholds, depending on the test frequency. The standard deviations of the discrepancy between ASSR and thresholds are larger than those between CERA and behavioral thresholds. Overall, mean deviations of ASSR and CERA from pure-tone behavioral thresholds are greatest in the normal hearing group and smallest in subjects with hearing levels at 90 dB HL or above. Compared to results obtained at 4000 Hz, ASSR and CERA at lower frequencies generally deviated greater from behavioral thresholds. Cumulative percentages of ears falling within an accuracy band at various test frequencies between ASSR/CERA and behavioral thresholds are presented in Figure 2. Overall results showed agreement within 15 dB in 90.0% of cases when ASSR thresholds were compared to behavioral thresholds and in 97.5% of cases when CERA thresholds were used.

Relationships between ASSR/ CERA and behavioral audiometric thresholds

Linear regression analysis was used to relate ASSR and CERA data to behavioural thresholds. Scatterplots of data are shown in Figure 3 with their regression formulae. These equations are also listed in Table 2 for ease of comparison. The intercepts represent the correction factors to be added to ASSR or CERA thresholds to predict behavioral thresholds and suggest that greater correction factors are required to predict behavioral thresholds from ASSR data than from CERA ones, consistent with above findings. The correction factors also increase with test frequency. The ‘x’ multiplication factor represents the slope of the regression line and suggests that CERA thresholds have a slightly better one-to-one correspondence with increasing behavioral thresholds than ASSR thresholds. The regression slopes are almost identical across test frequencies for CERA, and increase with frequency for ASSR. There is a wider dispersion of data when hearing was normal or close to normal, particularly for ASSR. The standard errors for prediction of behavioral thresholds shown in Table 2 suggest slightly smaller standard errors associated with CERA than ASSR measures.

Discussion

Prediction of pure-tone thresholds using CERA

This study showed that interpretations of CERA thresholds among the two experienced audiologists are very consistent because their judgments were mostly within 5 dB and not more than 10 dB. As they had been blinded to the hearing thresholds of the participants, bias in the interpretation of CERA results had been avoided.

Prediction of behavioral thresholds using CERA is more accurate when the hearing loss is greater, consistent with previous research by Tsui et al (2002). The mean CERA-behavioral threshold difference (-1.8 to 7.9 dB from 500 to 4000 Hz) obtained in this study is larger than those reported by Prasher et al (1993) and Tsui et al (2002) (-4.3 to -1.0 dB) at 1000 Hz and 2000 Hz, but smaller than the 10 dB across frequencies reported by Hoth (1993). Differences in findings between this and other studies may be attributed to two reasons. First, because the audiologists who had determined CERA thresholds in this study were blinded to the participants’ behavioral thresholds, bias was reduced. At the same time, selecting a response at or near threshold is less likely as poor waveforms are often recorded at these levels. Audiologists may exercise more caution in result interpretation by selecting more certain responses, thus causing bias in the form of elevated response levels. Second, unlike clinical practice where results from several averagings are used to determine thresholds when preceding ones are of doubt, two runs were administered at each level and no other repeats were allowed; only repeatable waveforms with more definite responses were used for analysis, others were discarded. Thus, there are greater deviations of CERA from behavioral thresholds in this study than previous research (Prasher et al, 1993; Tsui et al, 2002). On the other hand, absolute differences between CERA and behavioral thresholds across studies are not the most important because correction factors can be applied to predict behavioral from CERA thresholds. The standard deviations of the differences between CERA and behavioral thresholds show the variations in differences across participants and are more important to note. In the present study, the standard deviations of the differences between CERA and behavioral thresholds are comparable to those reported by Prasher et al (1993) and smaller than those reported by Tsui et al (2002) and Hoth (1993) suggesting that blinding the judges did not result in more accurate prediction but a slow down of test interpretation process and potentially a burden in human resources because another audiologist needs to be involved. This procedure is not advocated in clinical practice.

Prediction of pure-tone thresholds using ASSR

ASSR thresholds are significantly different from pure-tone behavioral thresholds. The mean difference between ASSR and behavioral thresholds is not more than 14 dB, which is in agreement with those reported by Dimitrijevic et al. (2002), Herdman and Stapells (2003) and Lins et al (1996) (see Table 3). The standard deviations of the differences are comparable to those reported by these same studies, but smaller than those reported by Hsu et al (2003). Subjects in the Hsu et al. study exhibited noise-induced hearing loss: reduced standard deviations may be related to the homogeneity of hearing loss. Consistent with results from

Cone-Wesson and Dowell et al (2002), Lins et al., (1996) and Rance et al. (1995), mean threshold differences across test frequencies are the greatest when hearing thresholds were within the normal range and the smallest when a severe to profound hearing loss was involved, possibly because recruitment has caused ASSR to be recorded at lower sensation level than when no hearing loss was present (Rance et al., 1995). In addition, mean threshold differences are smaller at 4000 Hz than at lower frequencies (500 and 1000 Hz) in those with hearing impairment. These findings are commensurate with those from previous studies (Cone-Wesson & Dowell et al, 2002; Herdman and Stapells, 2003; Hsu et al, 2003).

The R-square values for the regression equations relating CERA/ASSR thresholds with behavioral thresholds are at .95 or above suggesting these equations predict pure-tone behavioral thresholds well. The R-square is a function of correlation coefficients and the results are consistent with findings from Herdman and Stapells (2003), Hsu et al (2003), and Rance et al (1995).

Overall, best correspondence between ASSR and behavioral thresholds are noted at higher frequencies (2000 and 4000 Hz), and slightly reduced at lower frequencies (500 and 1000 Hz) when hearing was within the normal range; and best when hearing loss increased to the profound range, consistent with findings from Hsu et al (2003) and Rance et al (1995). Large individual variations are noted when predicting behavioral thresholds from ASSR ones.

Comparisons between CERA and ASSR

CERA thresholds are closer to behavioral thresholds than ASSR ones. CERA also predicted hearing thresholds to within 10 dB in greater percentage of cases than ASSR did. The difference in the degree of deviations between these measures may be attributed to response generation sites. CERA is generated within the primary and secondary auditory cortex in the superior and lateral surface of the superior temporal gyrus (Hyde, 1997); and the generation site of ASSR depends on the modulation frequency between 20 Hz and 200 Hz. To generate ASSR response from late cortical structures associated with the primary auditory cortex, Cone-Wesson & Dowell et al (2002) recommended using a modulation frequency of 20 Hz or less, instead of 40 Hz that was used in the present study. The regression equations also show that larger correction factors are needed to convert ASSR to behavioral thresholds than from CERA to behavioral thresholds. Differences in methods used to determine the presence of a response may also contribute to these differences in results between CERA and ASSR. The determination of the presence of a CERA response is largely based on waveform morphology and automated computer detection was used in ASSR. In this study, greater number of cases were predicted to within ± 10 dB of behavioral thresholds using CERA than ASSR. How accurate the regression equations established in this study would predict behavioral thresholds in clinical situations is unclear and is expected to vary with individual difference, experience of audiologists judging CERA thresholds and whether prior knowledge of behavioral thresholds is available.

Clinical Implications

While ASSR and CERA can both be used to predict behavioral thresholds quite accurately, the following points must be noted when using these techniques clinically. Firstly, although both ASSR and CERA thresholds are close to behavioral thresholds, a correction factor of 0 to 15 dB should be applied when predicting pure-tone behavioral thresholds. Due to variations in results across individuals, a single correction factor cannot be used. Prediction of thresholds in normal hearing listeners may be less accurate. Therefore, the degree of hearing loss should not be determined based on ASSR or CERA alone.

Second, the application of CERA is limited to alert individuals where responses are more robust and reliable (Hyde et al, 1986); the application of CERA in sleeping or sedated infants or children has not been researched in detail. In contrast, ASSR modulation frequency can be altered to allow assessment of participants in natural sleep or sedation (Cone-Wesson & Dowell et al, 2002; Cohen et al, 1991). Therefore, ASSR may be better in the assessment of difficult-to-test population.

Third, because CERA elicits neural activity in the thalamic-cortical segment, it evaluates higher order auditory cortical processing, including auditory sensitivity and the ability to discriminate sounds (Naatanen & Picton, 1987) but ASSR as evaluated here cannot be used to differentiate between peripheral or retrocochlear pathology, or for examining central auditory processing function (Rance & Briggs, 2002).

Fourthly, time efficiency should be considered when selecting the assessment tool to use. CERA testing and result interpretation generally take longer to complete than ASSR. In the current study, CERA testing at the four frequencies took about half an hour longer to complete than ASSR. Cone-Wesson & Dowell et al (2002) took an average of 104 seconds to detect an ASSR response, and Rance et al (1995) took a total of 30 to 60 minutes to complete testing at four frequencies in both ears. It took 4 minutes to detect a CERA response, and a total of 60 to 90 minutes for a complete test in the study by Musiek & Lee (1999). Automated computer detection algorithms is used to determine whether an ASSR response is present, thus reduces the amount of time for result interpretation. As it is difficult to judge the presence of a CERA response near threshold (Hyde et al, 1986), more time may be spent on repeating and interpreting measurements. Thus, ASSR testing appeared to be more time efficient than

CERA testing.

Finally, because automated computer detection algorithms are measured to determine the presence of ASSR responses, test bias is essentially eliminated. However, results from this study show that inter-tester reliability is good when testers are experienced in interpreting CERA responses. Because statistical analysis has not been used for evaluation CERA responses, whether it improves the reading of responses at low sensation level is unclear.

Summary of findings and conclusion

The present study showed a close agreement between CERA and behavioral thresholds and between ASSR and behavioral thresholds. Results confirmed findings from previous studies (e.g. Tsui et al (2002) and Cone-Wesson & Dowell et al (2002)) that hearing thresholds are more accurately predicted when the degree of hearing loss increases and as test frequency increases. CERA is slightly more accurate in threshold prediction than ASSR but the difference may not be clinically important. The large variances in findings across individual participants make the use of a single correction factor in threshold prediction impossible.

Unlike previous research (e.g. Hyde et al, 1996; Prasher et al, 1993; Herdman and Stapells, 2003; Hsu et al, 2003), the present study examined the relationships of CERA and ASSR with behavioral thresholds in the same participants, reducing the effect of intersubject variability on the comparisons – this study provides a better measure of true differences between the two measures. While inter-tester reliability should be examined further, clinicians should note the shortcomings of each measure when deciding whether to use ASSR or CERA and when interpreting data.

Table 1

Mean (standard deviation) differences in dB between ASSR/CERA and behavioral audiometric thresholds at various test frequencies.

Hearing level	Test	500 Hz	1000 Hz	2000 Hz	4000 Hz
0 – 25 dB HL	ASSR	13.4 (10.8)	18.6 (10.0)	21.8 (9.0)	17.1 (10.3)
	CERA	9.2 (8.7)	9.1 (7.2)	11.3 (6.6)	12.1 (8.1)
30 – 55 dB HL	ASSR	12.9 (7.4)	14.3 (7.0)	12.3 (8.4)	2.4 (10.6)
	CERA	7.1 (8.3)	8.3 (5.2)	4.7 (10.3)	-2.6 (13.7)
60 – 85 dB HL	ASSR	11.3 (9.3)	14.6 (7.7)	9.3 (10.0)	-.71 (13.8)
	CERA	5.5 (6.6)	8.6 (7.7)	8.2 (8.5)	-2.9 (19.2)
90+ dB HL	ASSR	1.5 (7.5)	2.9 (8.4)	4.4 (6.8)	1.7 (6.9)
	CERA	-2.0 (5.4)	2.1 (5.4)	5.9 (6.9)	-9.4 (9.7)
Overall	ASSR	11.0 (9.9)	13.7 (10.1)	12.3 (10.3)	4.3 (12.0)
	CERA	6.1 (8.5)	7.5 (6.9)	7.9 (8.4)	-1.8 (15.0)

Table 2

Linear regression formulae and standard errors of the estimates in regression equations used to predict behavioral thresholds from CERA or ASSR thresholds.

	CERA			**ASSR**		
Frequency	**Regression**	**Standard error**		**Regression**	**Standard error**	
(Hz)	**Equation**	**Slope**	**Constant**	**Equation**	**Slope**	**Constant**
500	y = 1.05x – 8.94	.03	2.05	y = 1.05x – 13.78	.04	2.59
1000	y = 1.03x – 9.44	.03	1.71	y = 1.09x – 19.74	.04	2.75
2000	y = 1.01x – 8.61	.03	2.19	y = 1.17x – 24.04	.04	2.76
4000	y = 1.05x – 11.06	.04	2.87	y = 1.16x – 24.30	.05	4.03

x = CERA or ASSR threshold
y = Predicted behavioral threshold

Table 3

Summary of mean (M) threshold differences and standard deviation (SD) in dB and correlations (r) between ASSR and behavioral thresholds in the present and previous studies.

	500 Hz		**1000 Hz**		**2000 Hz**		**4000 Hz**	
	M (SD)	**r**	**M (SD)**	**r**	**M (SD)**	**r**	**M (SD)**	**r**
Present study	11 (10)	.96	14 (10)	.97	12 (10)	.97	12 (13)	.95
Cone-Wesson, Dowell et al (2002)	13 (4)	--	--	--	--	--	7 (4)	--
Dimitrijevic et al (2002)	14 (11)	.85	5 (9)	.94	5 (9)	.95	9 (10)	.95
Herdman & Stapells (2003)	14 (13)	.75	8 (9)	.89	10 (10)	.88	3 (10)	.85
Hsu et al (2003)	18 (4)	.86	19 (3)	.92	17 (3)	.94	12 (5)	.95
Lins et al (1996)*	9 (9)	.72	13 (12)	.70	11 (10)	.76	12 (13)	.60
Rance et al (1995)	-- (10)	.97	-- (9)	.98	-- (7)	.99	-- (5)	.99
Rance et al (1998)*	6 (7)	.97	4 (6)	.98	3 (6)	.99	6 (7)	.99

-- indicates that data was not reported

* Includes data from children

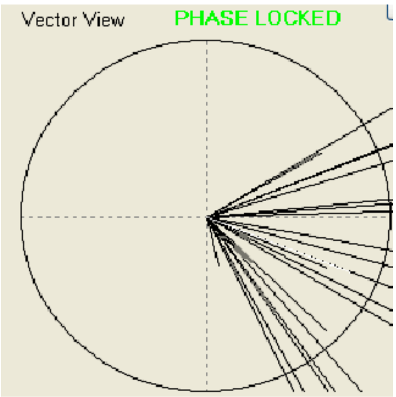
Figure Legends

Figure 1. Examples of (a) phase-locked, (b) random, and (c) noisy response.

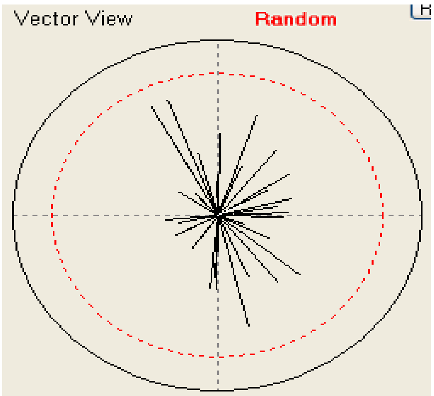
Figure 2. Distributions of ASSR versus behavioral audiometric thresholds, and CERA versus behavioral audiometric thresholds for 63 ears at: (a) 500 Hz, (b) 1000 Hz, (c) 2000 Hz, and (d) 4000 Hz. The solid lines represent linear regression lines for predict behavioral thresholds from CERA/ASSR thresholds and the R-squares are reported below each figure.

Figure 3. Cumulative percentage of ears within an accuracy band at various test frequencies between ASSR/CERA and behavioral thresholds.

(a) phase-locked



(b) random



(c) noisy

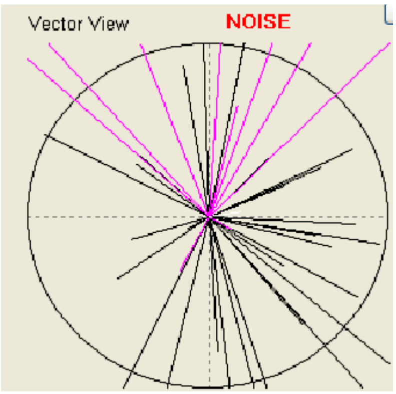
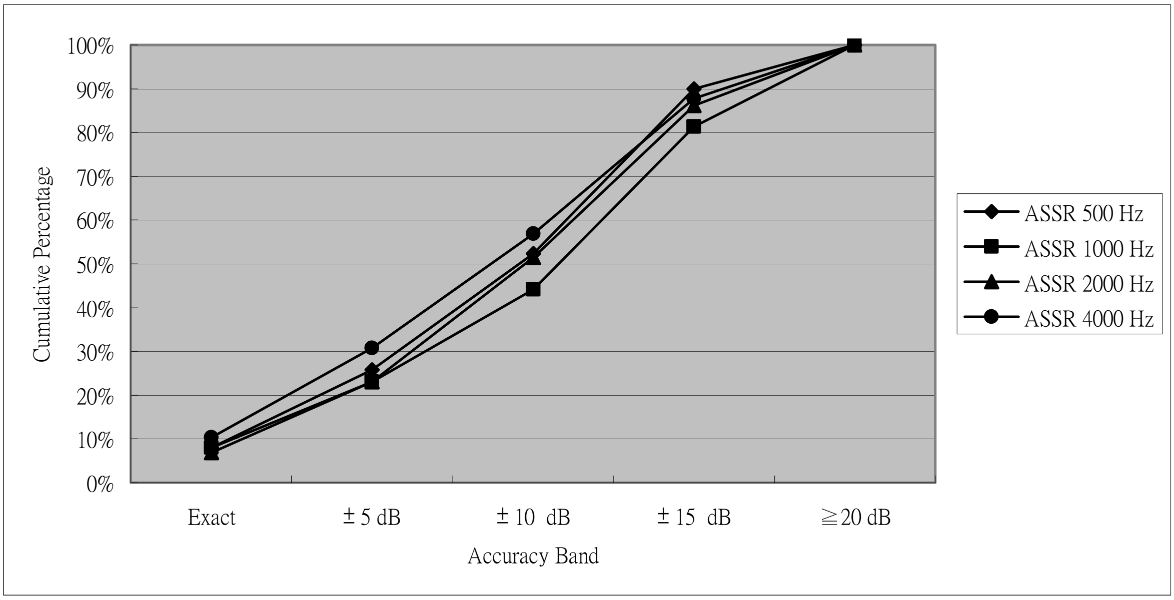


Figure 1. Examples of (a) phase-locked, (b) random, and (c) noisy response



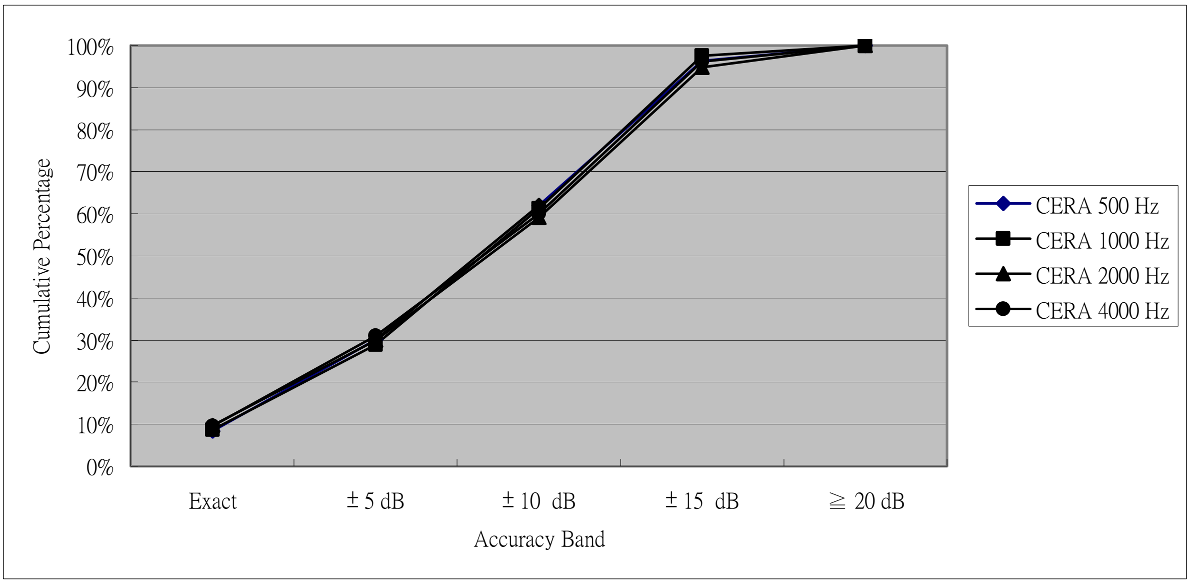
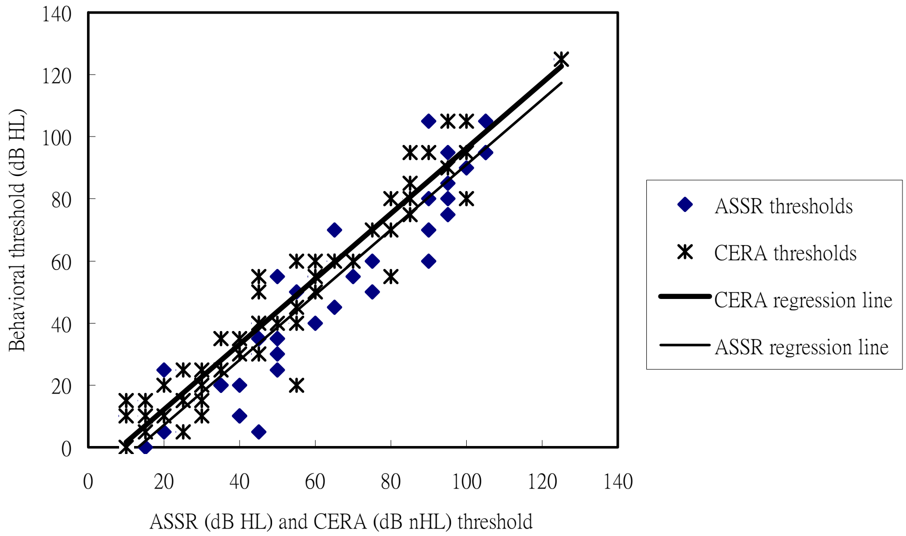


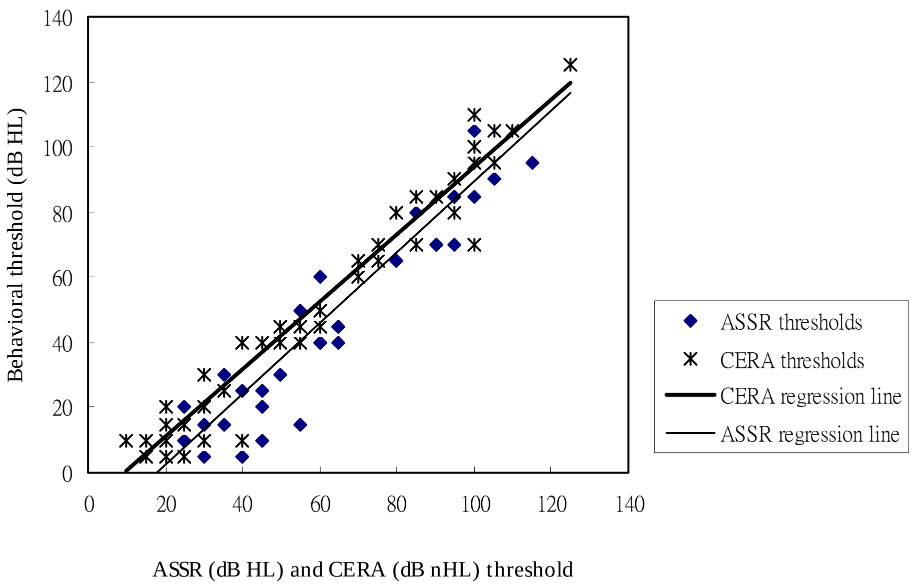
Figure 2. Cumulative percentages of ears within an accuracy band at various test frequencies when ASSR/CERA was used to predict behavioral thresholds.

(a) 500 Hz



CERA: (R^2 = .96, p<.01)
ASSR: (R^2 = .96, p<.01)

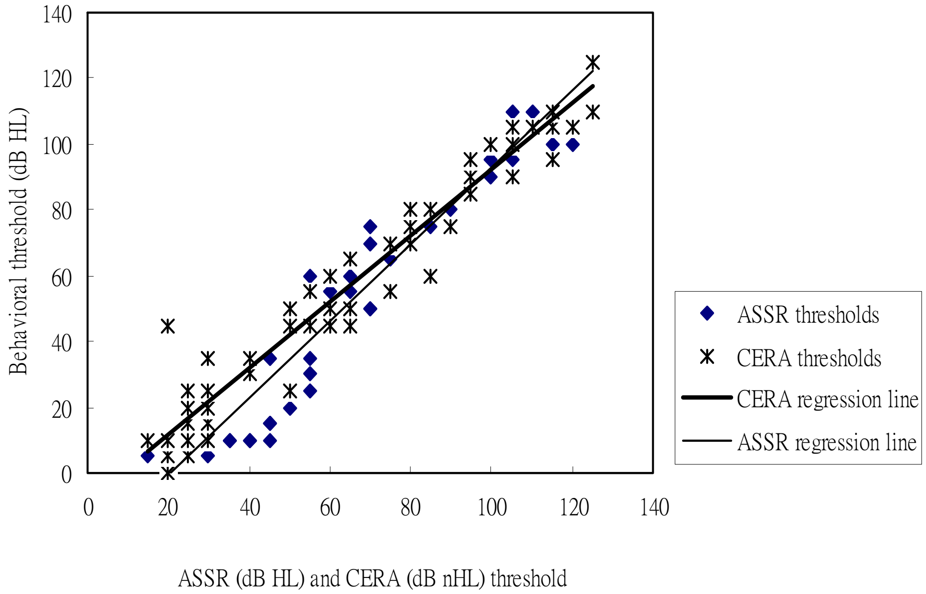
(b) 1000 Hz



CERA: (R^2 = .98, p< .01)
ASSR: (R^2= .97, p<.01)

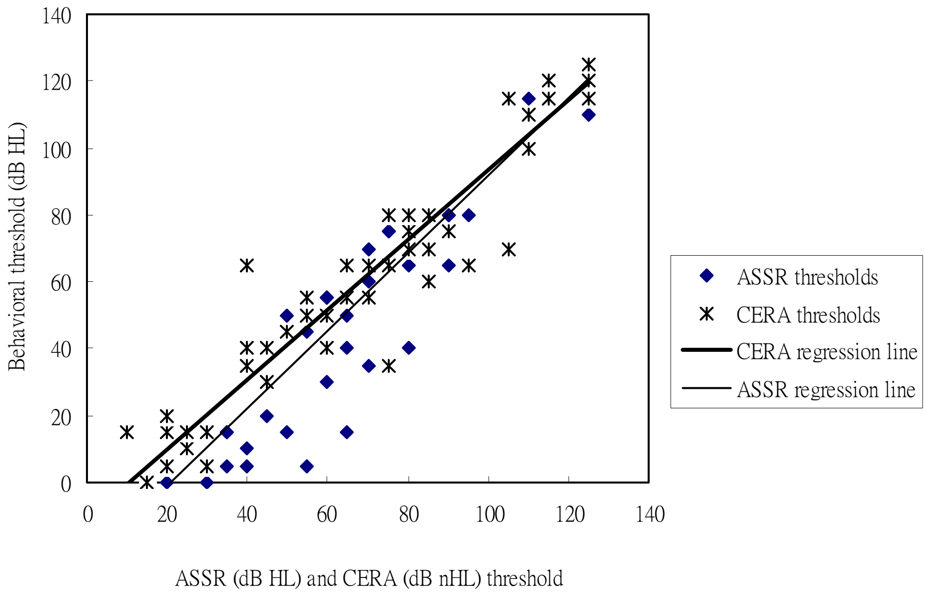
Figure 3. Distributions of ASSR versus behavioral audiometric thresholds, and CERA versus behavioral audiometric thresholds for 63 ears at: (a) 500 Hz, (b) 1000 Hz, (c) 2000 Hz, and (d) 4000 Hz. The solid lines represent linear regression lines for predict behavioral thresholds from CERA/ASSR thresholds and the R-squares are reported below each figure.

(c) 2000 Hz



CERA: (R^2 = .97, p<.01)
ASSR: (R^2 = .97, p<.01)

(d) 4000 Hz



CERA: (R^2 = .97, p<.01)
ASSR: (R^2 = .95, p<.01)

Figure 3. Cont'd

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