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Estimating Air-Bone Gaps Using Auditory Steady-State Responses

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Abstract
Auditory steady-state responses (ASSR) were recorded using stimuli presented both via air conduction (AC ASSR) and bone conduction (BC ASSR) in 10 normal-hearing subjects with different degrees of simulated conductive hearing losses. The ASSR-estimated ABG (air-bone gap) was compared with the ABG measured using traditional pure-tone audiometric procedures. Reproducibility of the BC ASSR electrophysiological thresholds was also assessed. Additionally, a group of five subjects with profound sensorineural hearing loss was used to establish stimulation levels in which the BC ASSR was contaminated by stimulus artifact. Results of this investigation showed that the ASSR and behavioral ABGs were strongly correlated with each other (r = .81). However, ASSR-estimated ABGs slightly overestimated the magnitude of the behavioral. Reproducibility of the BC ASSR electrophysiological thresholds was good. Data from the five subjects with profound hearing loss, however, demonstrated that the levels where stimulus artifact became problematic were relatively low. This means BC stimulation may be appropriate only for subjects with normal or mildly impaired cochlear sensitivity.

Key Words: Auditory evoked potentials, air-bone gap, auditory steady-state response

Abbreviations: ABG = air-bone gap; AC = air conduction; AM = amplitude modulation; ASSR = auditory steady-state response; BC = bone conduction; FM = frequency modulation

Sumario
Se registraron respuestas auditivas de estado estable (ASSR) utilizando estímulos presentados por conducción aérea (AC ASSR) y por conducción ósea (BC ASSR) en 10 sujetos normo-oyentes, con grados diferentes de pérdida conductiva simulada. La brecha aéreo-ósea (ABG) estimulada por ASSR se comparó con la ABG medida utilizando procedimientos audiométricos tonales tradicionales. Se evaluó también la reproducibilidad de los umbrales electrofisiológicos obtenidos por vía ósea (BC ASSR). Además, se utilizó un grupo de cinco sujetos con hipoacusia sensorineural profunda para establecer los niveles de estimulación en que los BC ASSR se contaminaban con artefactos del estímulo. Los resultados de esta investigación mostraron que las

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brechas aéreo-óseas (ABG) conductuales u obtenidas por ASSR se correlacionaban fuertemente (r = 0.81). Sin embargo, las ABG estimadas por ASSR sobreestimaban levemente la magnitud de los resultados conductuales. La reproducibilidad de los umbrales electrofisiológicos de los BC ASSR fue buena. Los datos de los cinco sujetos con hipoacusia sensorineural profunda, sin embargo, demostraron que los niveles a los que el artefacto en el estímulo se vuelva problemático fueron relativamente bajos. Esto significa que la estimulación por vía ósea puede ser apropiada solamente para aquellos sujetos con sensibilidad coclear normal o apenas levemente alterada.

Palabras Clave: Respuestas auditivas de estado estable, brecha aéreo-ósea, potenciales evocados auditivos

Abreviaturas: ABG = brecha aéreo-ósea; AC = conducción aérea; AM = modulación de la amplitud; ASSR = respuestas auditivas de estado estable; BC = conducción ósea; FM = modulación de la frecuencia

Several recent studies have explored the relationship between auditory steady-state response (ASSR) electrophysiological thresholds and audiometric behavioral thresholds for normal-hearing and hearing-impaired listeners (Rance et al, 1995; Cone-Wesson et al, 2002; Vander Werff et al, 2002a). Most of these studies have focused on patients with sensorineural hearing losses. Relatively few studies have reported data obtained from patients with conductive hearing losses or reported results of testing obtained using bone conduction rather than air conduction. If the ASSR is to become more widely accepted into clinical practice, it will be important to understand how conductive hearing loss affects the ASSR as well as the consequences of using bone- rather than air-conduction transducers. This is particularly true given that we do not always know if an individual child whom we see for electrophysiologic assessment of hearing has a conductive component to his or her hearing loss. This report focuses on the advantages and disadvantages of using a bone-conduction vibrator to evoke the ASSR.

BONE-CONDUCTION ASSR

To date, only three reports have been published describing ASSR measures obtained using bone conduction. Lins and colleagues (1996) presented multiple stimuli with 100% amplitude modulation (AM) through a RadioEar B-71 bone vibrator placed on the forehead in eight normal-hearing adults. A 60 dB SPL sensorineural hearing loss was simulated by passing a 65 dB SPL white noise through a 0.5 to 1.5 kHz band-pass filter (48 dB/octave) to the test ear. Behavioral and steady-state responses were determined for the stimulus presented alone and with the masking noise. For the masked condition, the difference between the air-conduction (AC) ASSR thresholds and the masked behavioral AC thresholds was 5 ± 5 dB. The masked ASSR BC (bone conduction) thresholds were 11 ± 5, 14 ± 8, 9 ± 8, and 10 ± 10 dB higher than the masked behavioral BC thresholds at 500, 1000, 2000, and 4000 Hz, respectively. They performed the ASSR BC experiments in normal-hearing subjects. The ASSR thresholds obtained via BC for these normal-hearing subjects were 26 ± 6, 28 ± 10, 33 ± 7, and 26 ± 11 above behavioral threshold levels at 500, 1000, 2000, and 4000 Hz, respectively. In this study, no mention was made of possible stimulus-related artifact coming from the bone vibrator, nor was the accuracy of air-bone gaps estimated using the ASSR evaluated.

Dimitrijevic and colleagues (2002) routed 100% AM plus 25% frequency modulation (FM) stimuli through the RadioEar B-71 bone vibrator placed on the forehead in 10 normal-hearing subjects. They used earphones plugged with plasticine to create a conductive hearing loss. They found that ASSR BC response amplitudes (combined across four frequencies) were larger than AC ASSR amplitudes, particularly for BC stimuli presented at relatively high intensity levels.

Again, these authors comment that they could not rule out possible contamination of the ASSR BC from stimulus artifact.

Cone-Wesson and colleagues (2002b) adapted the "sensorineural acuity level" technique (Jerger and Tillman, 1960; Dirks, 1973) to estimate ASSR BC thresholds in 39 infants with risk factors for hearing losses. They initially recorded ASSR thresholds for a 1 kHz amplitude modulated tone burst presented via air conduction. They then repeated this measure using a 1 kHz amplitude modulated sinusoid presented via air conduction at a level 10 dB above the previously determined ASSR threshold. They then introduced bone-conducted, narrow-band noise at levels that were just high enough to mask the ASSR. They reason that the amount of bone-conducted noise needed to mask the ASSR may distinguish between infants and children with conductive hearing losses and those with sensorineural hearing losses and, therefore, may be used to estimate bone-conduction thresholds. Results of this study showed that this technique correctly identified six subjects with suspected conductive hearing losses from five subjects with suspected sensorineural hearing losses. However, behavioral air-bone gaps were not available for these subjects. While it appears promising and while it does not require that the ASSR stimulus be presented via BC, the accuracy of this technique needs verification in a population with known audiometric behavioral thresholds.

We have known for many years that it is possible to distinguish between conductive and sensorineural hearing losses using the auditory brainstem response (ABR). The major difference between an ABR recorded from a subject with a conductive hearing loss as opposed to a subject with a sensorineural hearing loss is that in the conductive case, the ABR will have elevated thresholds, prolonged absolute response latencies, but normal interpeak latencies (Mendelson et al, 1979; Fria and Sabo, 1980; Hall and Grose, 1993). The software used to record the ASSR has focused almost exclusively on determining if a response is present or absent based on statistical criteria. Estimating latency of the ASSR can be problematic because of the continuous nature of the stimulus. With current software, there is not an easy way to determine if the ASSR, like the ABR, will have prolonged response latencies in subjects with conductive hearing loss.

It is also possible to record the ABR using a bone-conduction rather than an air-conduction transducer. However, this is not done routinely in many clinics because the use of the bone-conduction vibrator results in significantly more stimulus artifact contamination problems than are routinely encountered with an air-conduction transducer (Kylen et al, 1982; Harder et al, 1983). Additionally, relatively few studies have been published showing ABR BC electrophysiological thresholds for large groups of subjects with known hearing losses (Hofmann and Flach, 1981).

Few studies have described how stimulus artifact associated with the use of a bone vibrator may affect the ASSR recordings. The presence of stimulus artifact in the ABR is typically determined by examining the time waveform of the averaged response. The software used most widely to record the ASSR is designed primarily to display the frequency spectrum and not the averaged time waveform of the recorded response. Therefore, it may not be as easy to determine if the ASSR is contaminated by stimulus artifact as it is to determine if the ABR is contaminated by stimulus artifact.

Finally, none of the studies published to date have explicitly focused on the relationship between the audiometric estimates of air-bone gap (ABG) and the ASSR-based estimates of ABG, or on the relative stability of the ASSR electrophysiological thresholds recorded via BC stimulation. Additionally, the three articles referenced above present group data and limited individual data. They do not focus explicitly on how stimulus artifact may affect the BC ASSR recordings. Those are the goals of this study.

SPECIFIC AIMS

The goals of this study are to examine AC and BC ASSR electrophysiological thresholds in subjects with different degrees of conductive hearing loss, to check the relationship between the size of the ABG estimated behaviorally and the size of the ABG estimated using the ASSR, and to evaluate the reproducibility of BC ASSR electrophysiological thresholds. Finally, a series of profoundly hearing-impaired subjects will be used to determine the levels at which stimulus artifact become problematic for the ASSR as recorded using a forehead bone-conduction vibrator.

Given that ASSR and pure-tone behavioral thresholds are well correlated, we hypothesize that the ASSR ABG will also be well correlated with the pure-tone ABG, and our ability to estimate bone-conduction thresholds in these subjects will not be limited by stimulus artifact contamination. The reproducibility of BC ASSR electrophysiological thresholds has not been reported, but the test-retest variability in the AC ASSR electrophysiological threshold data has been described as low (Maurizi et al, 1990). We hypothesize, therefore, that the reproducibility of BC ASSR electrophysiological thresholds will be high if the stimulation and recording conditions are well controlled.

METHODS

Subjects

Ten adult subjects with hearing sensitivity better than 25 dB HL at 500, 1000, 2000, and 4000 Hz were recruited to participate in this study. Three subjects were male, and seven subjects were female. The average age of these normal-hearing subjects was 29 years (SD = 6 years). None of these subjects had a history of middle-ear pathology, and none of these subjects had air-bone gaps of >10 dB at the time of testing.

Five subjects with bilateral profound sensorineural hearing losses were also recruited from the University of Iowa Hospitals and Clinics to participate in this study. All of these subjects were cochlear implant users; however, their cochlear implant was turned off during all the ASSR test sessions. Two were male and three were female. The average age of these profoundly hearing-impaired subjects was 45 years (SD = 17 years). None of these subjects had a history of middle-ear pathology. None of these subjects could detect the presence of the ASSR stimulus presented via BC at the maximum stimulation limits.

Stimulus Parameters and Calibration

The MASTER system v.1c software was used to record the multiple auditory steady-state responses. A GSI 16 audiometer was used to present the stimulus via Eartone 3A insert earphones and Radioear model B-71 bone vibrator. The level of the modulated AC stimuli produced by the MASTER system was measured using a Larson & Davis system 824 model sound level meter coupled to an NBS-9A 2cc coupler. These dB SPL values were then transformed to dB HL according to the ANSI S3.6 (1996) standards. The level of the modulated BC stimuli were recorded with the aid of a Larson & Davis system 824 artificial mastoid model AMC 493 mounted on an AEC100 NBS-9A 6cc coupler. The weight on the top of the artificial mastoid was adjusted to provide a force of 4–5 Newton on the bone vibrator. These measurements were compatible with the standards reported in ANSI S3.6 (1996). Calibrations of the BC stimuli were carried out individually for 500, 1000, 2000, and 4000 Hz. BC stimuli at these four frequencies were routed together into a combined stimulus and then transmitted to the bone vibrator.

ASSR Stimulus Parameters

Carrier frequencies were 500, 1000, 2000, and 4000 Hz. Modulation frequencies were 78, 83, 87, and 92 Hz for 500, 1000, 2000, and 4000 Hz, respectively. The carrier frequencies were 100% amplitude modulated and combined prior to being presented via BC or AC to the subject (see Figure 1). When BC stimuli were used, a masking white noise was presented at a level of 80 dB SPL to the nontest ear via air conduction to assure that the recorded responses did not reflect contributions from the contralateral ear.

Figure 1 shows the time waveforms and frequency spectra of the AC and BC stimuli used in this study. The upper left graph presents an example of the AC stimulus time waveform, which is a combination of the four carrier frequencies modulated with four different modulation frequencies. The upper right panel displays the corresponding frequency spectra of the AC stimulus. In the frequency spectrum, a central peak and two side bands can be identified for each individual carrier frequency. Different amplitude levels can be observed among these four carrier frequencies because the level of each carrier frequency was calibrated in dB HL individually with the standards reported in ANSI S3.6 (1996), and the amplitude of the frequency spectrum was displayed in dB V in

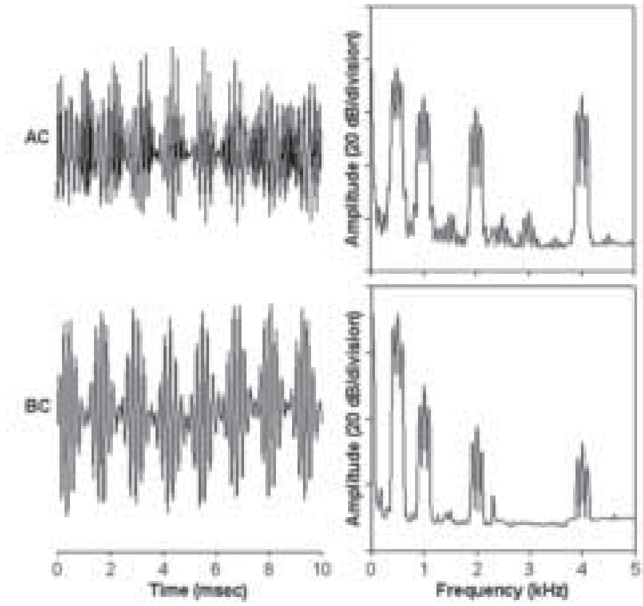

Figure 1. Time waveforms and frequency spectra of the AC and BC stimuli are shown. The time waveforms of the stimuli used in this study are shown on the left. The frequency spectra of the corresponding stimulus time waveforms are shown on the right. A central peak and two side bands can be identified for each carrier frequency.

this figure. Some harmonic distortion was observed but only at levels at least 20 dB smaller than those of the carrier frequencies. The lower two graphs show the combination time waveform and frequency spectrum of the BC stimulus. The level of each carrier frequency was calibrated in dB HL individually using the standards reported in ANSI S3.6 (1996). A central peak and two side bands were observed as well. Some harmonic distortion in the BC stimuli was also observed but again was recorded only at levels 20 dB smaller than those of the carrier frequency.

ANSI specifications require that the headband used to couple the bone vibrator to the forehead provides a static force of 5.4 ± 0.5 Newton (ANSI S3.6, 1996). However, there is no recommended procedure for measuring the force applied with the headband (Smith and Foster, 1997). We used a locally constructed headband to couple the bone vibrator to the forehead of our subjects. The applied force of the headband-vibrator system was determined for each subject with an Ohaus pull-type spring scale model 8003-PN (capacity x resolution is 10 Newton x 0.25 Newton). This tension gauge was attached to the headband. The headband was displaced laterally from the skull with the tension gauge until the vibrator contact surface was observed to just barely separate from the skin of the forehead. We adjusted the headband to achieve a total applied force of 4–5 Newtons.

ASSR Recording Parameters

Three disposable surface recording electrodes were applied to all subjects at the high forehead as well as on the mastoids. All electrode impedances were under 3 kOhm at 10 Hz. The responses were amplified using an electrically isolated, high impedance head stage amplifier with a gain of 10. An additional gain of 1000 was provided by a Dataq Bioamplifier Model BMA-931. The recording software added an additional gain of 5 making the total amplification of 50,000. The recorded EEG activity was then filtered using an analog band-pass filter of 30–300 Hz (12 dB/Octave) prior to being digitized.

The ASSR responses were recorded in epoch 1.024 sec in length. An individual epoch was rejected if it contained voltages greater than ±20 μV. During each recording condition, usually fewer than 30 epochs were rejected. A total of 256 epochs were collected for each intensity level. The stimulus levels were systematically increased from a low intensity level in steps of 5 dB until a significant response had been obtained. ASSR electrophysiological thresholds were defined as the lowest level at which two statistically significant ASSR responses were recorded. Two ASSR recordings were collected for stimulation levels near threshold. The MASTER software uses an F-statistic to determine whether the spectral component in the response at the modulation frequency is significantly above the level of noise in the 126 bins surrounding that modulation frequency. Any response with a p value $<$ 0.05 was considered to be a statistically significant response.

Procedures

In order to create ABGs of varying magnitudes at 500, 1000, 2000, and 4000 Hz, two different materials (epoxy, lamb's wool) were inserted into the insert earphone tips. ABGs of 30–60 dB were created by inserting a small amount of epoxy to block the tip of the insert earphone. Smaller ABGs were created by inserting a plug of lamb's wool into the tip of the earphone. Generally, lamb's wool resulted in an ABG on the order of 15–30 dB.

Initially, pure-tone AC and BC behavioral thresholds were obtained to ensure that each subject's hearing thresholds were better than 25 dB HL at 500, 1000, 2000, and 4000 Hz. A Radioear model B-71 vibrator was secured with a headband, and the headband-vibrator system was placed on the forehead with a force of 4–5 Newtons. An epoxy-plugged insert earphone was placed in the external ear canal of the test ear (left ear), while an unplugged insert earphone was placed in the nontest ear (right ear).

This montage was kept in place throughout both the pure-tone and ASSR evaluations. Responses were recorded to the following protocol: (1) Estimate epoxy-plugged pure-tone AC and BC audiometric behavioral thresholds using contralateral masking, (2) Estimate epoxy-plugged AC and BC ASSR behavioral thresholds, (3) Estimate epoxy-plugged AC ASSR electrophysiological thresholds, (4) Estimate epoxy plugged BC ASSR electrophysiological thresholds. The whole process was repeated using an insert earphone plugged with lamb's wool. The whole recording procedure typically took two hours. During this time, subjects were seated in a reclining chair and asked to rest or sleep. Potential subjects were initially screened to insure that they could relax sufficiently to allow efficient data collection. For most subjects the recording procedures required two sessions. These sessions were never separated by more than two weeks.

For the cochlear implant subjects, only BC ASSR electrophysiological thresholds were recorded; otherwise, the procedure outlined above was followed. An ascending approach was used. Because these subjects had bilateral profound losses and could not hear the BC stimuli, the levels that yielded a significant response were interpreted as stimulus artifact.

RESULTS

Figure 2 shows an example of the AC ASSR recordings obtained from an individual with normal hearing using an insert earphone that was plugged with lamb's wool. The left column of this figure shows the frequency spectra of the response at five different stimulus intensity levels. The number on each graph represents the stimulus level in dB HL. The downward arrows indicate responses that are statistically significant at a p = .05 level for each of the four carrier frequencies. A different modulation frequency was used for each carrier frequency. The

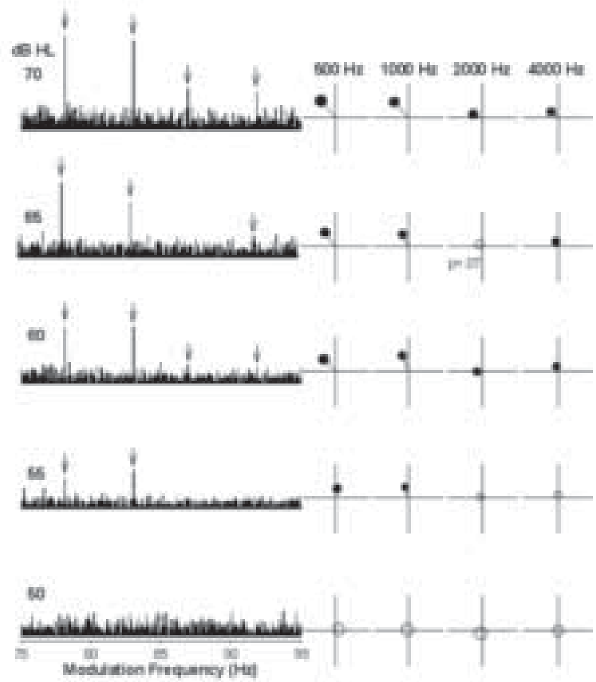

Figure 2. Frequency spectra and polar plots of the AC ASSR recordings from an individual with normal hearing obtained using an insert earphone that was plugged with lamb's wool. The frequency spectra of the response recorded at five different stimulus intensity levels are shown on the left. The downward arrows indicate responses that are statistically significant at a $p < 0.05$ level. Polar plots of these responses at 500, 1000, 2000, and 4000 Hz, respectively, are shown on the right side of the figure. The diameter of the circle represents the 95% confidence interval, and the distance from the center of the circle to the origin represents the amplitude of the response. A filled circle represents a statistically significant response ($p < 0.05$). Open circles represent nonstatistically significant responses.

Table 1. Bone-Conduction ASSR Thresholds Recorded from Five Cochlear Implant Users with Bilateral, Profound, Sensorineural Hearing Losses

	500 Hz	1000 Hz	2000 Hz	4000 Hz
Subject 1	> 55	45	55	> 55
Subject 2	55	45	>55	>55
Subject 3	55	30	55	>55
Subject 4	45	30	50	50
Subject 5	55	30	55	55
Average	53	36	54	53

lowest modulation frequency was used for 500 Hz and the highest for 4000 Hz.

The right column of Figure 2 shows the corresponding vector plots at 500, 1000, 2000, and 4000 Hz, respectively. The distance from the center of the circle to the origin represents the amplitude of the response, and the diameter of the circle represents the 95% confidence interval. If the circle does not include the origin, it is considered to be statistically significant and is plotted as a filled circle. If the circle does include the origin, it is not considered to be a statistically significant response and is plotted as an open circle.

ASSR threshold was defined as the lowest level at which at least two of three replications were statistically significant and where no more than one statistically insignificant response was obtained at suprathreshold levels. For example, in Figure 2 the ASSR threshold for the 2000 Hz stimulus was defined as 60 dB HL because two successive replications (not shown in the figure) at that stimulation level revealed a significant response, despite the fact that there was a recording obtained at 65 dB HL that did not reach significance ($p < 0.05$). This criterion is more stringent than some other researchers have used and therefore may lead to a somewhat greater difference between ASSR thresholds and pure-tone behavioral thresholds than has been reported in the literature. However, use of this relatively stringent criterion resulted in more stable ASSR thresholds and is similar to criteria used by other investigators (Dimitrijevic et al, 2002).

Table 1 shows the BC ASSR electrophysiological thresholds recorded from five cochlear implant subjects with bilateral profound sensorineural hearing losses. These subjects all had profound hearing losses and were not able to hearing the BC ASSR stimuli. Table 1 shows the lowest levels where we obtained a significant BC ASSR. We interpreted this as evidence of stimulus artifact. The maximum output level for the bone vibrator was set according to the average where we recorded responses from these five cochlear implant subjects. The average levels where BC ASSR responses were recorded from these bilateral, profound, sensorineural hearing loss subjects were 53, 36, 54, and 53 dB HL at 500, 1000, 2000, and 4000 Hz, respectively. All the BC ASSR stimuli used in this study were restricted within the average BC levels.

Figure 3 illustrates the distribution of the AC, BC ASSR and pure-tone AC, BC thresholds. For the group of subjects tested, the left column shows the data obtained using inserted earphone tips plugged with epoxy, and the right column displays the similar data obtained using inserted phone tips plugged with lamb's wool. Each panel presents the data collected at the four different test frequencies. These data are displayed using box plots. The upper and lower boundaries of the box indicate the 25th and 75th percentiles, respectively. The solid line within the box marks the median, and the dotted line represents the mean. Whiskers above and below the box indicate the 95th and 5th percentiles, respectively. As expected, ASSR and pure-tone thresholds are elevated when AC stimuli are used. The amount of elevation is bigger for epoxy than lamb's wool. In general, the mean ASSR electrophysiological thresholds are elevated compared to the behavioral thresholds. In order to have a better comparison between BC ASSR and pure-tone BC thresholds, the bone-conduction vibrator was placed on the forehead for both the BC ASSR and pure-tone BC threshold measurements. As a result, the pure-tone BC behavioral thresholds in these 10 normal-hearing subjects are all

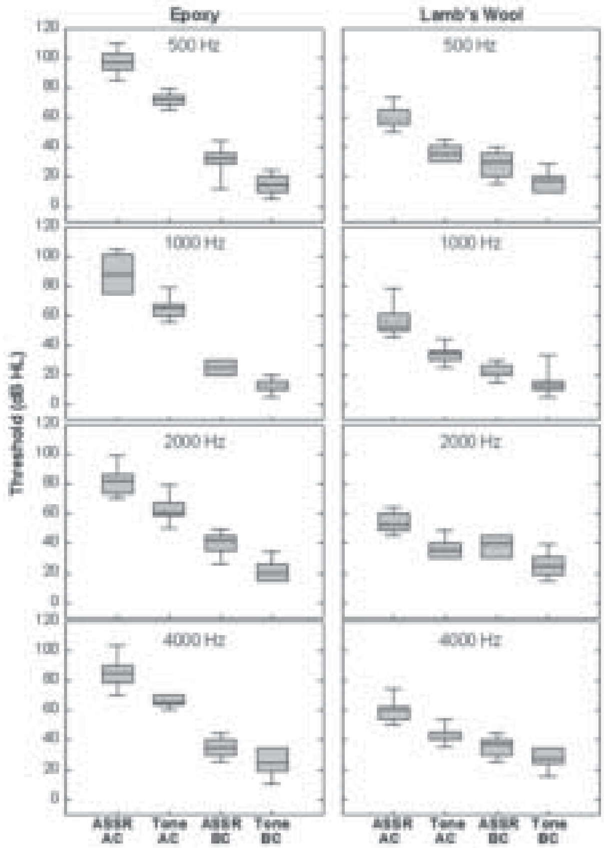

Figure 3. This figure shows the distribution of AC ASSR thresholds and BC ASSR thresholds as well as behavioral measures of AC and BC thresholds at each of the different test frequencies. The four panels in the left column show data obtained using epoxy. The four panels in the right column show data obtained using lamb's wool. These data are displayed using box plots. The upper and lower boundaries of the box indicate the 25th and 75th percentiles, respectively. The solid line within the box marks the median, and the dotted line represents the mean. Whiskers above and below the box indicate the 95th and 5th percentiles, respectively.

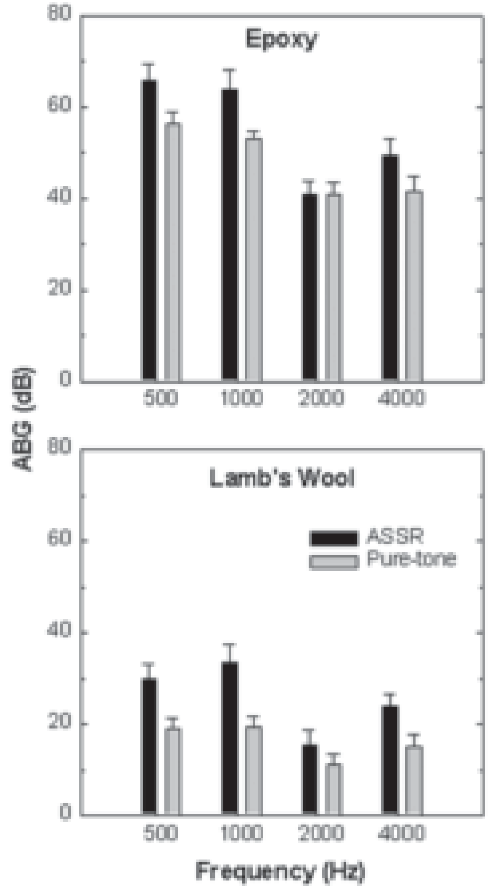

Figure 4. Average ABGs obtained using ASSR and pure-tone audiometric techniques are shown for each of the four different test frequencies. The upper panel displays data obtained using earphone tips plugged with epoxy; the lower panel displays data obtained using earphone tips plugged with lamb's wool. In each panel, the group mean is shown along with one standard error above the mean value.

higher than what would be expected for normal-hearing subjects if mastoid placement was used.

Figure 4 displays the average ABG as measured using ASSR and pure-tone audiometric procedures for the four different test frequencies. The ABG is derived when BC threshold is subtracted from AC threshold, that is, ABG = AC - BC. The upper panel displays the data obtained using epoxy plugged earphone tips, which created average pure-tone ABGs of 57, 53, 41, and 42 dB at 500, 1000, 2000, and 4000 Hz, respectively. The lower panel displays the data obtained using earphone tips plugged with lamb's wool, which created average pure-tone ABGs of 19, 20, 11, and 15 dB, respectively. The ASSR-estimated ABG was 10, 13, 2, and 9 dB bigger than pure-tone ABG at 500, 1000, 2000, and 4000 Hz, respectively. In each panel of Figure 4, the error bars indicate one standard error above the mean.

Figure 5 displays the correlation between ASSR-estimated ABGs and ABGs measured using behavioral techniques. In this figure, results from all four different test frequencies and for both media conditions, epoxy and lamb's wool, was pooled. The abscissa represents the ASSR ABG, and the ordinate represents the pure-tone ABG. The solid line

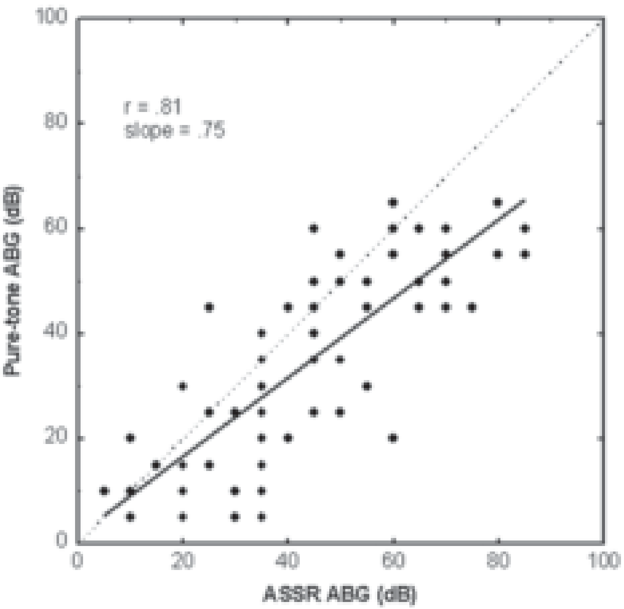

Figure 5. Correlation between ASSR ABGs and the ABGs measured using behavioral techniques is shown. Data from all the four test frequencies and for both media conditions (epoxy and lamb's wool) has been pooled together. The solid line represents the result of the linear regression; the dotted line has a slope of 1 between ASSR ABG and pure-tone ABG.

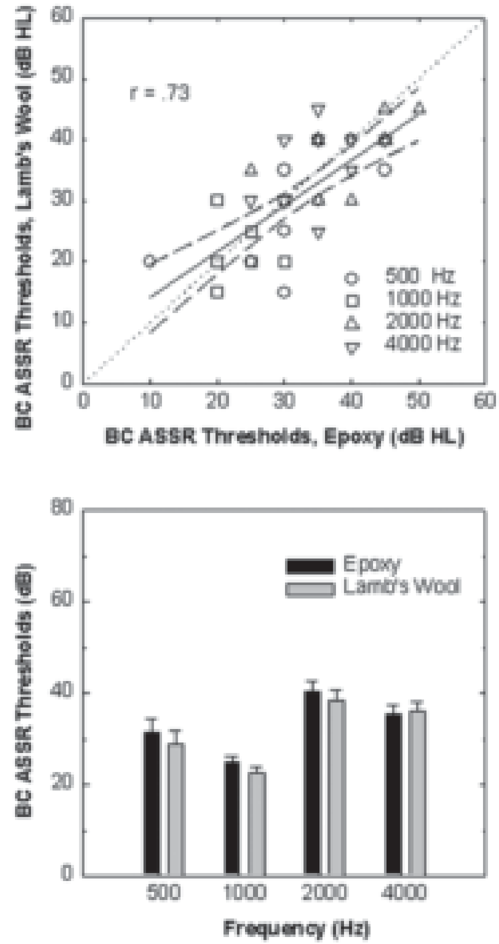

Figure 6. Comparison between epoxy and lamb's wool BC ASSR electrophysiological thresholds is shown. The upper panel shows the individual comparison between the BC ASSR thresholds obtained by using insert earphones plugged with epoxy and the corresponding BC ASSR thresholds obtained using lamb's wool. Data from the four different test frequencies are represented with different symbols. The solid line represents the results of linear regression analysis. The upper and lower dashed lines represent the 95% and 5% confidence intervals, respectively. The lower panel shows the mean and standard error from the same data, epoxy and lamb's wool. Note the mean difference between the two BC ASSR thresholds is less than 3 dB at the four different test frequencies.

represents the results of linear regression analysis. The correlation coefficient is 0.81, and the slope of the regression line is 0.75. The dotted line represents the slope of 1 between ASSR ABG and pure-tone ABG.

The upper panel of Figure 6 is a scatter plot of the individual data showing the comparison between BC ASSR electrophysiological thresholds obtained using earphone tips plugged with epoxy and BC ASSR electrophysiological thresholds obtained using earphone tips plugged with lamb's wool. In this figure, data from the four different test frequencies are represented with different symbols. The solid line represents the results of linear regression analysis obtained by pooling together data collected at all four test frequencies. No effort has been made to indicate where multiple data points overlap. The upper and lower dashed lines represent the 95% and 5% confidence intervals, respectively. The correlation coefficient is 0.73.

The lower panel of Figure 6 shows the same data plotted in bar graph form. The mean difference between the two BC ASSR electrophysiological thresholds is 3, 3, 2, and 0 dB at 500, 1000, 2000, and 4000 Hz, respectively. The error bars represent the standard error around the mean. Generally, given the known variance in BC behavioral thresholds obtained using standard audiometric procedures and the fact that 5 dB steps sizes were used to estimate threshold, we would consider this variability acceptable.

DISCUSSION

The main goal of this study was to examine the relationship between ASSR-estimated ABG and audiometric estimates of ABG in subjects with different degrees of simulated conductive hearing losses. The results of this study show that ASSR ABG and the audiometric estimates of ABG were strongly correlated with each other (see Figure 5). There has been very little published describing the efficacy of the BC ASSR. Lins and colleagues (1996) reported a strong correlation between BC ASSR electrophysiological thresholds and audiometric behavioral thresholds for eight subjects with a range of BC thresholds. However, the accuracy of ASSR-estimated ABG was not addressed directly. Cone-Wesson and colleagues (2002b) adapted the "sensorineural acuity level" technique and correctly identified six subjects with suspected conductive hearing losses (e.g., flat tympanograms, etc.) from five subjects with suspected sensorineural hearing losses. However, they did not report behavioral measures of the actual air-bone gap for these subjects. The results of the present study agree with previously published reports in that the ASSR-estimated ABGs in this study were strongly correlated with audiometric ABGs in subjects with simulated conductive hearing losses. One limitation of the current study, however, was that none of the subjects had an actual conductive hearing loss. Future work assessing the accuracy of ASSR-estimated ABGs should be conducted in subjects with varying degrees of conductive or mixed loss.

A secondary goal of this study was to evaluate the stability of BC ASSR electrophysiological thresholds and to determine the levels at which stimulus artifact radiated by the BC transducer may become problematic for the ASSR. Bone-conduction thresholds are known to depend both on the location of the bone vibrator (mastoid or forehead), whether or not the external ear canals are occluded (Harrell, 2001), as well as on the coupling force between the bone vibrator and the head (Lau, 1986). In the present study, in order to limit variability of the BC measures, the force of the bone vibrator on the forehead was calibrated and adjusted to 4–5 Newton. The bone vibrator was kept on the forehead, and the external ear canals were occluded throughout both the pure-tone and ASSR threshold evaluations so small variations in placement should not affect these two measures differently. Laukli and Fermedal (1990) examined the reproducibility of pure-tone audiometric BC thresholds in groups of normal-hearing subjects. They found that the pure-tone audiometric BC thresholds have a high degree of test-retest precision with mean differences of less than 2.5 dB. McDermott and colleagues (1991) examined the reliability of masked high-frequency BC thresholds in 95 normal-hearing subjects. They found that the high-frequency BC thresholds are reliable. Results of the present study show that the mean difference in epoxy and lamb's wool BC ASSR electrophysiological thresholds is 3, 3, 2, and 0 dB at 500, 1000, 2000, and 4000 Hz respectively (see Figure 6). We acknowledge that the BC electrophysiological threshold might be slightly affected by the amount of occlusion effect. However, results of the current study support that the reproducibility of the epoxy and lamb's wool BC ASSR electrophysiological thresholds is good and acceptable, which is down to less than 3 dB. No attempt was made on the present study examining the high-frequency BC ASSR electrophysiological thresholds (e.g., frequencies > 4000 Hz). As a result, no comparison can be made on the issue of high-frequency BC ASSR electrophysiological thresholds.

No data were found in the literature evaluating the effects of BC stimulus artifact on BC ASSR electrophysiological thresholds. However, Dimitrijevic (2002) mentioned possible artifact contamination coming from the bone vibrator in a BC ASSR growth function where the slope changed when the BC stimuli were above 30 dB HL. They applied ipsilateral AC white noise to mask the BC ASSR responses and found that the bone vibrator caused very little artifact in their study. However, it was possible that their higher number of false positive ASSR above 30 dB HL stimuli was caused by the contamination of stimulus artifact. Many authors have reported significant contamination of ABR measures when the BC transducer rather than the AC transducer is used (Schwartz et al, 1985; Stuart et al, 1993). Results of the present study show that the level where BC stimulus artifact can cause a significant BC ASSR was 53, 36, 54, and 53 dB HL at 500, 1000, 2000, and 4000 Hz, respectively. These levels are relatively low. Above these levels, significant ASSR responses were recorded even though the subject could not hear the BC stimulus. We have interpreted this as evidence of contamination of the ASSR by stimulus artifact. If standard BC transducers are used with forehead placement, BC stimulus intensity levels should be kept below these levels to avoid false positive BC ASSR. Future research evaluating the feasibility of developing an electrically shielded BC vibrator is needed. Additionally, a larger scale of normative data would be necessary in order to have a better understanding of the effects of bone vibrator stimulus artifact on BC ASSR measures.

If contamination of the BC ASSR by stimulus artifact is unavoidable, an alternate approach may be to use the "sensorineural acuity level" technique, which does not require ASSR stimulus be presented via bone vibrator. In order to have an estimate of ABG in sensorineural acuity level technique, AC ASSR electrophysiological thresholds should be obtained in two different conditions, with and without masking noise that is introduced via BC. While this should eliminate the problem of stimulus artifact at the modulation frequency, it may not be ideal because it will be relatively time consuming. If the BC ASSR is to become a viable clinical tool, validation of this procedure in subjects with known AC and BC behavioral thresholds is needed.

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