Effects of Bone Oscillator Coupling Method, Placement Location, and Occlusion on Bone-Conduction Auditory Steady-State Responses in Infants

Susan A. Small, Jennifer L. Hatton, and David R. Stapells

Objective: **The aim of these experiments was to investigate procedures used when estimating bone-conduction thresholds in infants. The objectives were: (i) to investigate the variability in force applied using two common bone-oscillator coupling methods and to determine whether coupling method affects threshold estimation, (ii) to examine effects of bone-oscillator placement on bone-conduction ASSR thresholds, and (iii) to determine whether the occlusion effect is present in infants by comparing bone-conduction ASSR thresholds for unoccluded and occluded ears.**

Design: **Experiment 1A: The variability in the amount of force applied to the bone oscillator by trained assistants (*n* = 4) for elastic-band and hand-held coupling methods was measured. Experiment 1B: Bone-conduction behavioral thresholds in 10 adults were compared for two coupling methods. Experiment 1C: ASSR thresholds and amplitudes to multiple bone-conduction stimuli were compared in 10 infants (mean age: 17 wk) using two coupling methods. Experiment 2: Bone-conduction ASSR thresholds and amplitudes were compared for temporal, mastoid and forehead oscillator placements in 15 preterm infants (mean age: 35 wk postconceptual age (PCA)). Experiment 3: Bone-conduction ASSR thresholds, amplitudes and phase delays were compared in 13 infants (mean age: 15 wk) for an unoccluded and occluded test ear. All infants that participated had passed a hearing screening test.**

Results: **Experiment 1A: Coupling method did not significantly affect the variability in force applied to the oscillator. Experiment 1B: There were no differences in adult bone-conduction behavioural thresholds between coupling methods. Experiment 1C: There was no significant difference between oscillator coupling method or significant frequency x coupling method interaction for ASSR thresholds or amplitudes in the young infants tested. However, there was a nonsignificant 9-dB better threshold at 4000 Hz for the elastic-band method. Experiment 2: Mean bone-conduction ASSR thresholds for the preterm infants were not significantly different for the temporal and mastoid placements. Mean ASSR thresholds for the forehead placement were significantly higher compared to the other two placements (12–18 dB higher on average). Mean ASSR amplitudes were significantly larger for the temporal and mastoid placements compared to the forehead placement. Experiment 3: There was no difference in mean ASSR thresholds, amplitudes or phase delays for the unoccluded versus occluded conditions.**

Conclusions: **Trained assistants can apply an appropriate amount of force to the bone oscillator using either the elastic-band or hand-held method. Coupling method has no significant effect on estimation of bone-conduction thresholds; therefore, either may be used clinically provided assistants are appropriately trained. For preterm infants, there are no differences in ASSRs when the oscillator is positioned at the temporal or mastoid placement. However, thresholds are higher and amplitudes are smaller for the forehead placement, consequently, a forehead placement should be avoided for clinical testing. There does not appear to be a significant occlusion effect in young infants; therefore, it may be possible to do bone-conduction testing with ears unoccluded or occluded without applying a correction factor, although further research is needed to confirm this finding.**

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It is important to obtain air- and bone-conduction thresholds in infants to distinguish between sensorineural, conductive, and mixed hearing losses, similar to assessment of adults. It is a relatively straightforward procedure to deliver a calibrated air-conduction stimulus to the infant or adult ear via earphones. For bone-conduction testing, however, producing a predictable output of energy at the skull, and ultimately to the cochlea, is more complicated because of a number of procedural factors. Important procedural factors include (i) oscillator coupling force and method (steel headband, elastic-band or hand-held), (ii) oscillator placement location on the head (temporal or frontal bone), and (iii) whether the bone-conduction testing is performed with ears occluded or unoccluded. Procedures are relatively standardized for estimating behavioral thresholds to bone-conducted stimuli in adults and children; the bone oscillator is positioned on the head of an adult or child using a steel headband that applies a constant force to the bone oscillator. In contrast, there are no standardized methods for bone-conduction testing in infants, only recommended "best

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

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practices"; many of which are based on assumptions rather than systematic investigation.

Because the bone oscillator sits on the surface of the skull, a sufficient and constant force is required to couple it to the head and to produce a calibrated output from the transducer. Amount of force and coupling method are therefore important issues. Also, the bone oscillator can be positioned in different locations on the skull, potentially affecting the intensity of the signal reaching the cochlea (Stuart, Yang & Stenstrom, 1990; Yang, Rupert & Moushegian, 1987). It is also well known, at least for adults, that occluding the ear canal while estimating bone-conduction thresholds significantly improves bone-conduction thresholds in the low frequencies, a change known as the occlusion effect (Tonndorf, 1966).

For behavioral testing with bone-conducted stimuli, the oscillator is coupled to the head using a steel headband to apply a constant force to the bone oscillator; the exact amount of force applied (approximately 400 to 500 g) will vary, depending on individual head size. To accommodate the smaller head size for older children, a smaller steel headband is used; the force generated is less than for larger adult heads and will also vary somewhat with the size of the child's head (Harrell, 2002; Wilber, 1979). The coupling force used is limited to some degree by patient comfort; however, behavioral thresholds to bone-conducted stimuli in older children and adults can usually be obtained in approximately 10 to 15 minutes with only minor discomfort from the steel headband.

Estimation of bone-conduction hearing thresholds in young sleeping infants using auditory-evoked potentials poses unique challenges. Infants have smaller heads than adults, precluding the use of the standard adult or child steel headband. Also, infants must remain asleep during testing; disturbing the infant as little as possible while positioning the oscillator is critical, as is minimizing the discomfort during a much longer testing time. One concern for bone-conduction testing is that the amount of force applied to the oscillator is consistent. Coupling the oscillator to the infant's head using an elastic band is currently the clinical method suggested by many because a known force can be applied to the elastic band and the amount of force can be verified using a spring scale (Yang & Stuart, 1990). It is important to keep in mind, however, that although many clinical settings use an elastic band to couple the oscillator to the head, the amount of force applied to the elastic band is not verified for practical reasons (i.e., the clinician does not want to use any "sleep time" to perform the verification step and does not want to risk waking the infant in the process of verifying the force level and re-adjusting the elastic band). Holding the oscillator in place by hand is also commonly done clinically because it is faster and is far less likely to wake up the infant than positioning an elastic band (which requires more manipulation of the infant's head). Another benefit of the hand-held method is that it is more comfortable for the infant because it can be easily removed and replaced between test conditions.

Despite the practical advantages of the hand-held method, its use has been discouraged (Yang & Stuart, 2000; Yang, Stuart, Stenstrom, & Hollett, 1991). This preference for one coupling method over the other, however, is based on assumptions. The two main assumptions made are (i) for the hand-held method, there is potential for the applied force to vary during testing resulting in an inconsistent output from the transducer (Yang et al., 1991) and greater variability in threshold, and (ii) pressing down on the superior surface of the oscillator by hand (i.e., mass loading it) will dampen the response characteristics of the bone oscillator (Wilber, 1979). However, bone-conduction responses in infants have never been compared using the elastic-band and hand-held methods.

There are adult calibration values for bone-conducted stimuli for different bone-oscillator placement locations on the skull (i.e., mastoid and forehead). On average, adult behavioral thresholds measured at the forehead are higher than at the mastoid by 14, 8.5, 11.5, and 8.0 dB at 500, 1000, 2000, and 4000 Hz, respectively (American National Standards Institute [ANSI], 1996). Bone-oscillator placement location has also been raised as an issue (Stuart et al., 1990; Yang & Stuart, 2000) when estimating bone-conduction thresholds in sleeping infants because of the potential for thresholds to differ, depending on where the oscillator is placed on the temporal (mastoid versus upper region) or frontal bone. When an elastic band is used to couple the oscillator to the skull, it is typically placed on the infant's temporal bone, posterior to the upper portion of the pinna; using the hand-held method, a variety of positions are possible.

There are some auditory brain stem response (ABR) data which have been interpreted to suggest that bone oscillator location does affect the response in infants (Yang et al., 1987). Yang et al. (1987) investigated the effect of oscillator placement (frontal/forehead, occipital, and temporal) on wave V ABR latencies to bone-conduction clicks for neonates, 1-yr-old infants and adults. Latency results were found to vary with both age of subject and oscillator placement. The temporal bone yielded significantly shorter latencies than either the occipital and frontal placements in the neonatal group and 1-yr-old group. Based on these latency differences, they estimated that signal attenuation in the neonates from the temporal to frontal placement ranged from 30 to 35 dB. In the 1-yr-old group, signal attenuation between the frontal and temporal placements was estimated to be between 20 to 25 dB. Attenuation from occipital to temporal was 15 to 20 dB for both infant groups. In contrast, the latency differences in adults were not significant, and the attenuation between oscillator placement was judged to be no more than 5 to 10 dB. This attenuation estimate in adults is smaller than the ANSI-1996 standards for mastoid and forehead placements discussed above, and the changes in signal attenuation as a function of location suggested by Yang et al. must be interpreted with caution for several reasons. First, they used click stimuli rather than frequency-specific stimuli, so they were unable to separate out any frequency-dependent effects of oscillator placement on attenuation. Second, they did not directly estimate ABR thresholds for the different placements or report ABR amplitudes, which are more related to threshold than latency measures. Third, the attenuation estimates were derived using latency-intensity functions; inaccurate attenuation estimates may result because latency is not linearly related to intensity (Picton, Stapells, & Campbell, 1981).

Stuart et al. (1990) further investigated the effect of oscillator placement on wave V latencies in infants by comparing different areas on the temporal bone (superior, supero-posterior, and posterior placements). They concluded that changing the location of the oscillator on the temporal bone produced significantly different wave V latencies in the neonate at both 15 and 30 dB nHL. Specifically, the posterior position (similar to the "mastoid" in the current study) yielded the shortest wave V latency, whereas the superior position yielded the longest latency. The supero-posterior position (similar to the "temporal placement" in the current study) yielded intermediate latency values. These latency differences were attributed to reflect greater signal attenuation as a function of distance from the cochlea (Stuart et al., 1990). Specifically, it was suggested that signal intensity reduces as the bone oscillator is moved farther away from the cochlea. Again, these findings were based solely on click-ABR latency data and the same limitations that are discussed above apply. Neither of these two placement studies compared bone-conduction threshold in infants at different oscillator placements on the skull, which is the important measure for clinical applications.

Correcting for the occlusion effect when estimating bone-conduction thresholds with occluded ears is also well described in adults (Dirks & Swindeman, 1967; Elpern & Naunton, 1963; Hodgson & Tillman, 1966; Small & Stapells, 2003). For insert earphones, behavioral thresholds to brief-tones improve by 3 to 5 dB at 500 to 1000 Hz (Small & Stapells, 2003), whereas pure-tone behavioral thresholds in the low frequencies (250 to 1000 Hz) improve by as much as 17 dB, depending on the insertion depth (Dean & Martin, 2000). As discussed earlier, any test protocol used to estimate thresholds in sleeping infants must be designed to minimize the possibility of waking the infant. Air-conduction thresholds are typically assessed using insert earphones, followed by bone-conduction testing (Stapells, 2000). Should the insert earphones be removed before assessing bone-conduction thresholds? It is important to know whether occluding the ears increases, decreases or has no effect on bone-conduction thresholds in infants. There are no studies that have investigated the occlusion effect in infants.

The objectives of this study were (i) to investigate the variability in the amount of force applied using the two common bone-oscillator coupling methods used in infants and to determine whether oscillator coupling method affects estimation of bone-conduction threshold in infants and adults, (ii) to examine the effects of bone-oscillator placement location on bone-conduction auditory steady-state responses (ASSR) thresholds and amplitudes in young infants, and (iii) to determine whether the occlusion effect is present in infants by comparing infant bone-conduction ASSR thresholds for unoccluded and occluded ears.

GENERAL METHODS

The current study was divided into three main experiments that investigated the effects of (1) bone-oscillator coupling method on the variability in the amount of force applied to the oscillator and its impact on estimation of bone-conduction thresholds in infants and adults, (2) bone oscillator placement location on ASSR amplitudes and thresholds in infants, and (3) occluding the ear canal on bone-conduction ASSR amplitudes, phase delays, and thresholds in infants. The General Methods section describes the methodology common to all experiments including: stimuli, calibration of stimuli, ASSR recording parameters, and ASSR data analyses. The specific details of the participants, experimental design, statistical analyses, and description of the results for each experiment are reported in separate sections.

Stimuli

All stimuli were bone-conducted tones presented to a Radioear B-71 bone oscillator that was held by hand or by elastic headband with approximately 400 to 450 g of force. The bone oscillator was placed on the temporal bone (high or low) or on the forehead, depending on the experiment. For the temporal-bone placement location, the left or right side was selected at random. Bone-conducted stimuli were presented at intensities 50 to –10 dB HL.

For all ASSR experiments, stimuli were sinusoidal bone-conducted tones with the carrier frequencies 500, 1000, 2000, and 4000 Hz that were 100%

amplitude and 25% frequency modulated at 77.148, 84.961, 92.773, and 100.586 Hz, respectively. The stimuli were presented simultaneously for all conditions tested (i.e., multiple). All ASSR stimuli were generated by the Rotman MASTER research system (John & Picton, 2000a), using a digital-to-analog (D/A) rate of 31,250 Hz then attenuated through either an Interacoustics AC40 clinical audiometer (laboratory) or Tucker-Davis Technologies HB6 and SM3 modules (laboratory) or Med-Associates ANL-918 attenuator [Neonatal Intensive Care Unit (NICU)]. Before the stimuli were attenuated, they were routed through a Stanford Research Systems Model SR650 to increase the gain of the stimulus by 10 dB. To estimate behavioral thresholds in adults in Experiment 1B, bone-conduction pure-tones were presented using an Interacoustics AC40 clinical audiometer.

Calibration

The bone-conduction stimuli were calibrated in Reference Equivalent Threshold Force Levels (RETFL) in dB re:1μN corresponding to 0 dB HL for the mastoid (ANSI S3.6–1996, 1996) by using a Brüel and Kjaer Model 2218 sound level meter and Model 4930 artificial mastoid. The oscillator was coupled to the artificial mastoid with 550 g of force.

ASSR Recordings

ASSRs were recorded with the use of the Rotman MASTER system. Three electrodes were used to record the electrophysiologic responses; the noninverting electrode was placed at the forehead, the inverting electrode was positioned midline at the nape of the neck, just below the hairline, and an electrode placed at the high forehead acted as ground. All interelectrode impedances were below 3 kOhm at 10 Hz.

The electroencephalogram (EEG) was filtered with the use of a 30- to 250-Hz filter (12 dB/oct) and amplified 80,000 times (Nicolet HGA-200A and Nic501A). The EEG was further filtered by using a 300-Hz low-pass antialiasing filter [NICU: Stanford Research Systems (115dB/oct); laboratory: Wavetek Rockland Model 852 (48 dB/oct)]. The EEG was then processed by using a 1250-Hz A/D conversion rate (Small & Stapells, 2004). Each EEG recording sweep was made up of 16 epochs of 1024 data points each (0.8192 sec per epoch) and lasted a total of 13.107 sec. Artifact rejection was set to eliminate epochs of electrophysiologic activity that exceeded ± 40 μV in amplitude to reduce contributions to the EEG caused by muscle artifact.

ASSRs were averaged in the time domain then analyzed online in the frequency domain using a Fast Fourier Transform (FFT). Weighted averaging was used (John, Dimitrijevic & Picton, 2001). The FFT resolution was 0.093 Hz, over a range of 0 to 250 Hz. Amplitudes were measured baseline-to-peak and expressed in nano-Volts (nV). An F ratio was calculated by MASTER to estimate the probability that the amplitude of the ASSR at the modulation frequency for each carrier frequency was significantly different from the average amplitude of the background noise in adjacent frequencies within ± 60 bins of the modulation frequency ("noise") (John & Picton, 2000a). A minimum of seven sweeps were recorded for each test condition. A response was considered to be present if the F ratio, compared with the critical values for F (2, 240), was significant at a level of $p < 0.05$ for at least two consecutive sweeps. A response was considered to be absent if $p \geq 0.05$ and the mean amplitude of the noise was less than 11 nV. Alternatively, a response was also considered to be absent when response amplitude was <10 nV and the p value was >0.30.

ASSR Data Analyses

Mean amplitude values were averaged across subjects, including ASSR amplitudes for responses that were not significant (except for part of the data analyses in Experiment 2). The phase values from MASTER were adjusted by adding 90° to yield the onset phase (John & Picton, 2000a). Onset phase values were then converted to phase delay by subtracting the onset phase value from 360°. Any phase-delay values that differed ≥180° from an adjacent measure were "unwrapped" by adding 360° to their value (John & Picton, 2000b). Phase values for ASSRs that were not significant were excluded from mean phase-delay calculations. Phase-delay values were averaged across subjects. Results are only reported if at least five subjects contributed to the mean.

Statistical Analyses

Comparisons of experimental conditions were made using two-way repeated-measures analyses of variance (ANOVA); case-wise deletion was applied when values were missing from the data sets.* The factors and levels for the ANOVAs performed for each exper-

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*For all data sets that had missing values, statistical analyses using case-wise deletion to handle missing data were compared to statistical analyses using two different methods for replacing the missing values [mean substitution and imputation based on adjacent values (Little & Rubin, 2002, pp. 3–40)]. The purpose of these comparisons was to ensure that case-wise deletion did not yield different statistical results compared with other strategies for handling missing data. No differences in the statistical results were found for any of the analyses; consequently, the statistical analyses that used case-wise deletion were considered unbiased.

iment are reported in each section. Huynh-Feldt epsilon-adjustments for repeated measures were made when appropriate. Newman-Keuls *post-hoc* comparisons were performed for significant main effects and interactions. The criterion for statistical significance was $p < 0.05$ for all analyses. The effect sizes for the main effects and interactions between factors were calculated as the percentage of variance in the scores (PV), where a PV of 0.01, 0.10 and 0.25 correspond to small, medium, and large effect sizes (Murphy & Myors, 2004, pp. 22-97).

Experiment 1: Bone-Oscillator Coupling Method (Elastic-Band Versus Hand-Held)

The purposes of this experiment were to investigate (i) how much the amount of force applied to the bone oscillator varied with coupling method and (ii) to determine whether bone-conduction thresholds obtained in infants and adults were different between coupling methods. This experiment was divided into three subexperiments: 1A, effect of coupling method on variability in force level applied to oscillator; 1B, effect of coupling method on adult behavioral thresholds; and 1C, effect of coupling method on infant ASSRs. The participants, procedures and a description of the results specific to each subexperiment will be presented separately.

Experiment 1A: Effect of Coupling Method on Variability in Force Level Applied to Oscillator

The purpose of Experiment 1A was to measure the variability in the amount of force applied to the oscillator by four different individuals, using the elastic-band and hand-held coupling methods.

Methods

Participants and Procedure • For this experiment, four adults (age range, 23 to 39 yr) were trained to couple the bone oscillator to the head using the elastic-band and hand-held coupling methods and are referred to as the assistants. The bone oscillator was placed on the temporal bone slightly posterior to the upper part of the pinna. The anterior longitudinal edge of the oscillator was oriented at an approximately 45° angle to the anterior/posterior plane so that the wire connecting the oscillator to the attenuator lay in a posterior/inferior direction. Assistants were instructed to apply the same force (425 ± 25 g) on the superior surface of the bone oscillator on an adult head, whether they used an elastic band or held the oscillator by hand. During a training period, each assistant was instructed to apply the target force to the oscillator in a group of 10 practice trials. After each practice trial, the assistant received feedback about the actual amount of force applied. For the elastic-band method, a spring scale was used to measure the applied force. For the hand-held coupling method, applied force was measured by placing the bone oscillator on a compressive spring scale and pressing down on the transducer with one or two fingers until the desired force was achieved. Feedback was provided for 10 consecutive practice trials for each of the coupling methods. During the testing period, after completing the training, the assistants applied the target force, without feedback, for an additional 10 "test" trials for each coupling method. For each of these test runs, the actual force levels applied were recorded and compared for each assistant and coupling method.

TABLE 1. Range, mean, and mean absolute deviation for force levels produced by four assistants trained to use the elastic-band and hand-held bone-oscillator coupling methods

	Coupling							
	EB				HH			
Assistant	Range	Mean	SD	MAD	Range	Mean	SD	MAD
1	425–575	483	49	58	360–450	400	32	33
2	325–490	409	61	54	340–500	436	52	41
3	350–525	440	54	40	375–550	479	51	64
4	400–600	490	70	75	360–460	405	35	35
All	325–600	455	66	57	340–550	430	52	43

MAD, mean absolute deviation from target; EB, elastic-band; HH, hand-held; SD, 1 standard deviation.
Target of 425 ± 25 g; 10 test trials each.

Statistical Analyses • A 2-way repeated measures ANOVA was performed comparing force levels produced across 10 test trials and between the two coupling conditions (elastic-band and hand-held). Four cases (i.e., the four assistants) were included in the analysis.

Results • As shown in Table 1, there were some differences noted in the force levels produced by the assistants. For assistants 1 and 4, the mean force applied tended to be more than the target force when using the elastic band method but less than the target force when using the hand-held method. The mean forces applied by assistants 2 and 3 tended to be more similar across coupling method. Using the elastic-band, assistants produced a wider range of forces and larger standard and mean absolute deviations. Across assistants, the mean force produced was essentially the same for the elastic-band and hand-held methods.

Figure 1 shows the errors in the force applied to the oscillator produced by each assistant as a cumulative percent of test runs for the two coupling methods. Using the hand-held method, most of the test runs (70%) were within 50 g of the target, and all were within 100 g of the target. Using the elastic band, only 60% of the test runs were within 50 g of the target and only 88% were within 100 g; 100%

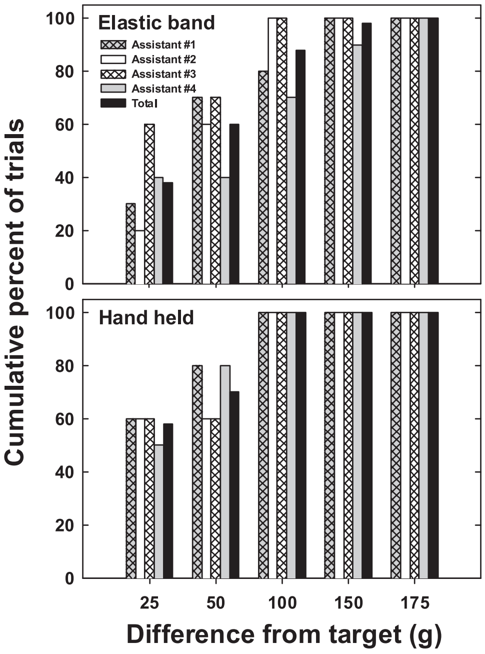

Fig. 1. Cumulative percentage of trials that resulted in errors produced, for example, 25, 50, 100, 150, and 175 g differences from the target force of 425 ± 25 g, for each individual assistant (*N* = 4; solid and striped bars) and across assistants (cross-hatched bars).

TABLE 2. Mean behavioral thresholds for 500-, 1000-, 2000- and 4000-Hz bone-conduction pure tones using elastic-band and hand-held coupling method in adults with normal hearing (*N* = 10)

	Coupling	500 Hz	1000 Hz	2000 Hz	4000 Hz
Threshold	EB				
(dB HL)	Mean	1.7	−0.3	11.5	−1.7
	SD	3.7	6.6	7.5	5.5
	N	10	10	10	10
	HH				
	Mean	1.5	2.3	8.7	0.1
	SD	4.9	4.1	5.4	5.0
	N	10	10	10	10
	Difference				
	Mean	0.2	−2.6	2.8	−1.8
	SD	4.2	3.9	4.5	5.6
	N	10	10	10.	10

EB, elastic-band; HH, hand-held; Difference, EB minus HH; SD, 1 standard deviation.

was only obtained within 175 g of the target. Results of an ANOVA comparing force levels across test trials and coupling method revealed no significant main effect of coupling method [F (1,3) = 0.577, p = 0.503, PV = 0.016] or test trial [F (9,27) = 1.649, p = 0.151, PV = 0.406] and no significant interaction between test trial and coupling method [F (9,27) = 2.016, p = 0.077, PV = 0.496].

Experiment 1B: Effect of Coupling Method on Adult Behavioral Thresholds

The purpose of Experiment 1B was to compare adult behavioral thresholds obtained for 500, 1000, 2000, and 4000 Hz, using the elastic-band and hand-held coupling methods.

Methods

Participants and Procedure • Ten adults (age range, 20 to 39 yr) with normal hearing (pure-tone air-conduction behavioral thresholds ≤25 dB HL for 500 to 4000 Hz) participated. Testing was conducted in a double-walled, sound-attenuated booth in the Human Auditory Physiology Laboratory at the University of British Columbia. On average, the noise levels in the sound-attenuated booth for one-octave-wide bands centered at 0.5, 1, 2, and 4 kHz were 12, 10, 10, and 12 dB SPL, respectively.

Behavioral thresholds were obtained using the elastic-band and hand-held coupling methods (assistants 1, 2, and 3) with ears unoccluded. The bone-oscillator placement location was the same as that used for Experiment 1A. The test order for coupling method was randomized. Bone-conducted pure tones (500 to 4000 Hz) were presented in 2-dB steps, using a bracketing technique. The starting intensity was randomly selected as 20, 30, or 40 dB HL. The lowest level at which 3/5 stimuli were detected was considered threshold. Behavioral thresholds across frequency and coupling methods were compared.

Statistical Analyses • A 2-way repeated measures ANOVA was performed comparing behavioral thresholds at 500, 1000, 2000 and 4000 Hz between coupling methods (elastic-band and hand-held). Ten subjects were included in the analysis.

Results • Adult mean behavioral bone-conduction thresholds for the elastic-band and hand-held coupling methods are shown in Table 2. Overall, the mean elastic-band minus hand-held threshold difference was only –1.4 dB. Results of an ANOVA indicated no significant main effect of coupling method [F (1,9) = 0.432, p = 0.527, PV = 0.010] and no interaction between coupling and frequency [F (3,27) = 3.275, p = 0.092, PV = 0.170]. The main effect for frequency [F (3,27) = 8.444, p = 0.0004, PV = 0.605] was significant and was explained by slightly poorer thresholds at 2000 Hz compared with the other frequencies as indicated by post hoc comparisons.

Experiment 1C: Effect of Coupling Method on Infant ASSRs

In Experiment 1C, ASSRs to bone-conducted stimuli were recorded in infants using the elastic-band and hand-held coupling methods to determine whether coupling method affects estimation of bone-conduction ASSR threshold in young infants.

Methods

Participants and Procedure • Ten normal-hearing post-term infants (age range, 0.5 to 38 wk; mean age, 17 wk) were recruited from the community. By parent report, all infants were healthy, normal infants with no history of middle ear disease. Three of the infants were screened with the use of an automatic auditory brain stem response (AABR) hearing screening test at 35 dB nHL. The hearing of the other infants was screened using a distortion-product otoacoustic emissions (DPOAE) screening test. The pass criterion for the DPOAE screening was a signal-to-noise ratio >5 dB at 2000, 3000 and 4000 Hz in both ears. Infants passed the AABR or DPOAE hearing screening in both ears and were considered to be at low risk for significant hearing loss and thus included in the study. Testing was conducted in the same sound-attenuating booth described above.

The oscillator was coupled to the infant's head using the elastic-band (assistants 1, 2, 3) and hand-held coupling methods (assistants 1 and 2).* The bone-oscillator placement location was the same as that used for Experiment 1A. The test order for coupling method was randomized. Multiple ASSR stimuli (500- to 4000-Hz carrier frequencies) were presented in 10-dB steps, using a bracketing technique. The starting intensity was randomly selected as 10, 20, 30, or 40 dB HL. The lowest level at which a response was present was considered threshold. Bone-conduction ASSR thresholds were compared across frequency and oscillator coupling method. Bone-conduction ASSR amplitudes at 30 dB HL for 500 and 1000 Hz and at 40 dB HL for 2000 and 4000 Hz were compared across frequency and coupling condition. A greater intensity was selected for 2000 and 4000 Hz than for 500 and 1000 Hz to compensate for poorer thresholds (approximately 10 dB) at these higher frequencies (Small & Stapells, 2006).

Statistical analyses • A 2-way repeated-measures ANOVA was performed comparing ASSR thresholds for 10 infants at 500, 1000, 2000 and 4000 Hz between coupling methods (elastic-band and hand-held). ASSR amplitudes at 30 dB HL for 500 and 1000 Hz and 40 dB HL at 2000 and 4000 Hz were also compared between coupling conditions using a 2-way repeated-measures ANOVA, however, as a result of case-wise deletion, only five infants were included in the analysis. An additional ANOVA comparing ASSR amplitudes at 30 dB HL at 500 and 1000 Hz only between coupling conditions was also performed; eight infants were included in the ANOVA as a result of case-wise deletion.

Results • Representative ASSR results to bone-conducted stimuli using the elastic-band and hand-held coupling methods are shown for a typical infant in Figure 2. For this 8-wk-old infant, there was no consistent effect of coupling method on ASSR thresholds. ASSR threshold was 30 dB poorer at 500 Hz and 10 dB better at 2000 Hz for the hand-held compared to the elastic-band coupling condition, and no difference in ASSR thresholds was found for the two coupling conditions at 1000 and 4000 Hz. Table 3 shows the mean bone-conduction ASSR thresholds for all infants. There was no significant difference between mean ASSR thresholds using the two coupling methods [$F\,(1,9) = 0.192$, $p = 0.67$, $PV = 0.004$]; however, there was a trend for ASSR thresholds at 4000 Hz to be slightly higher using the hand-held method compared with the elastic-band coupling method [coupling method x frequency interaction: $F\,(3,27) = 2.791$, $p = 0.06$. $PV = 0.161$].

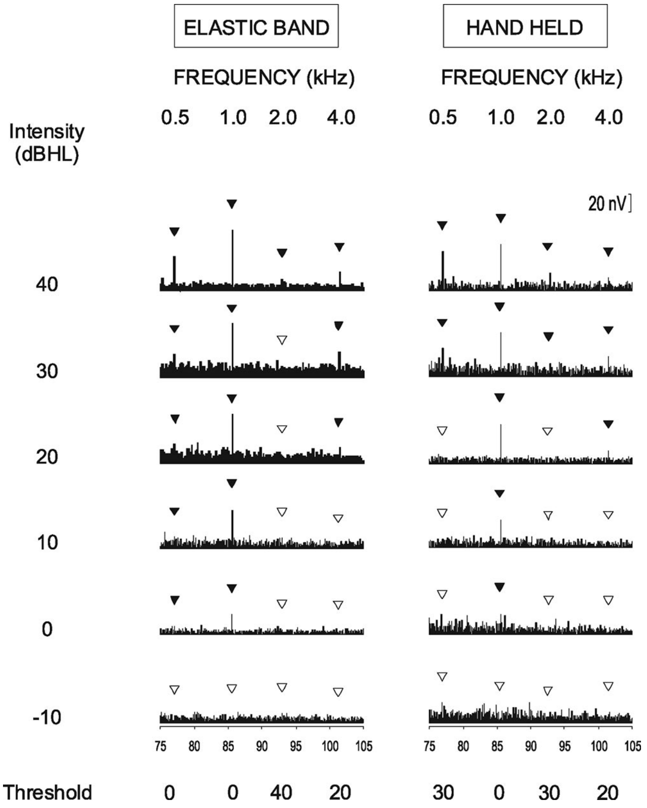

Fig. 2. Representative bone-conduction ASSRs for an individual post-term infant (8 wk) for the elastic-band and hand-held coupling methods. Shown are amplitude spectra resulting from FFT analyses (70 to 101 Hz) of the ASSRs. Filled triangles indicate responses that differ significantly ($p < 0.05$) from the background noise. Open triangles indicate no response ($p \geq 0.05$ and EEG noise <11 nV). Threshold is defined as the lowest intensity that produced a significant response.

As shown in Table 4, infant mean ASSR amplitudes at 30 db HL (500 and 1000 Hz) and 40 dB HL (2000 and 4000 Hz) were not significantly different for the elastic-band and hand-held coupling methods [$F\,(1,4) = 0.027$, $p = 0.878$, $PV = 0.001$]. However, there was a significant interaction between coupling method and frequency [$F\,(3,12) = 3.951$, $p = 0.036$,

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*Assistant 4 was not available to participate in this study.

TABLE 3. Mean ASSR thresholds for 500-, 1000-, 2000- and 4000-Hz bone-conduction carrier frequencies using elastic-band and hand-held coupling method in infants with normal hearing (N = 10; age, 2 to 10 mo)

	Coupling	500 Hz	1000 Hz	2000 Hz	4000 Hz
Threshold (dB HL)	EB				
	Mean	14.0	6.0	26.0	13.0
	SD	14.3	8.43	9.7	11.6
	N	10	10	10	10
	HH				
	Mean	14.0	1.0	25.0	22.0
	SD	14.3	7.4	7.1	7.9
	N	10	10	10	10
	Difference				
	Mean	0.0	5.0	1.0	–9.0
	SD	15.6	5.3	7.4	12.9
	N	10	10	10	10

EB, elastic-band; HH, hand-held; Difference, EB minus HH; SD, 1 standard deviation.

$PV = 0.497$]; post hoc comparisons indicated no elastic-band versus hand-held differences in ASSR amplitudes at the same carrier frequency. Mean ASSR amplitudes at 30 dB HL for 500 and 1000 Hz were not significantly different for coupling method [$F(1,7) = 2.231, p = 0.179, PV = 0.04$] and there was no significant interaction between coupling method and frequency [F (1,) = 0.002, p = 0.967, PV = 0.0004].

EXPERIMENT 2: EFFECT OF BONE-OSCILLATOR PLACEMENT LOCATION ON INFANT ASSRS

The purpose of this experiment was to determine if different placement locations of the bone oscillator on the skull affect ASSRs recorded to bone-conducted stimuli in preterm infants. The three oscillator placements investigated in this study included (i) the temporal bone slightly posterior to the upper part of the pinna, (ii) the lower portion of the temporal bone which will later develop into the mastoid bone, and (iii) the middle of the forehead. The placements are referred to as temporal, mastoid, and forehead.

TABLE 4. Auditory steady-state response mean amplitudes elicited by bone-conduction stimuli presented at 30 dB HL for 500- and 1000-Hz and at 40 dB HL for 2000-Hz and 4000-Hz carrier frequencies using elastic-band and hand-held coupling method in infants with normal hearing (N = 6 to 9; age, 2 to 10 mo)

	Coupling	500 Hz	1000 Hz	2000 Hz	4000 Hz
Amplitude (nV)	EB				
	Mean	41.0	59.2	24.5	36.3
	SD	21.3	19.5	12.6	15.8
	N	9	9	6	6
	HH				
	Mean	30.5	54.5	36.9	32.8
	SD	16.3	18.5	21.6	17.1
	N	9	9	7	7
	Difference				
	Mean	5.8	5.4	–12.6	9.0
	SD	15.3	17.1	16.3	11.2
	N	8	8	5	5

EB, elastic-band; HH, hand-held; Difference, EB minus HH; SD, 1 standard deviation.

Methods

Participants and Procedures • Fifteen preterm infants from a NICU participated. They ranged in age from 32 to 43 wk postconceptional age (PCA), with a mean age of 34.5 wk PCA. All infants were medically stable at time of test and had a mean (1 SD) Apgar score of 7.4 (2.6) at birth. All of these infants were screened by using an automatic AABR hearing screening test at 35 dB nHL. Infants passed the AABR hearing screening in both ears and were considered to be at low risk for significant hearing loss and thus included in the studies.

Testing of preterm infants was performed at the bedside in the NICU. Infants were tested with ears unoccluded. Ambient acoustic noise was likely to affect the results when recording ASSRs in the NICU. Average ambient noise levels in the NICU measured at two different time points using one-third–octave-wide bands were 52, 51, 60, 58, 50, 36, and 47 dB SPL at 0.125, 0.5, 1, 2, 4, and 8 kHz, respectively. The overall A-weighted noise level in the NICU was 65 dB SPL. To reduce the impact of high ambient noise in the NICU, recording of ASSRs was paused when the background acoustic noise was excessively high (e.g., when sink taps were running near the infant's bassinet).

ASSRs were first elicited to bone-conducted stimuli presented at the temporal bone using the hand-held coupling method at a starting intensity of 40 dB HL (30 dB HL for 2 of 15 infants). ASSRs were then recorded, in random order at the mastoid and forehead, to stimuli presented at 40 dB HL. ASSR threshold was then determined, always beginning with the temporal placement, using a bracketing technique with a final step size of 10 dB. The order of threshold search for the mastoid and forehead placements was randomized. If a response did not reach significance at the highest intensity (50 dB HL), threshold was arbitrarily assigned a value of 60 dB HL.

Statistical analyses • Comparison of ASSR threshold for 500, 1000, 2000 and 4000 Hz and for the three bone-oscillator placement locations (temporal, mastoid and forehead) was done using a 2-way repeated measures ANOVA. After case-wise deletion, nine preterm infants were included in the analysis of ASSR threshold. ASSR amplitudes (all responses) for 500, 1000, 2000 and 4000 Hz were compared for three bone-

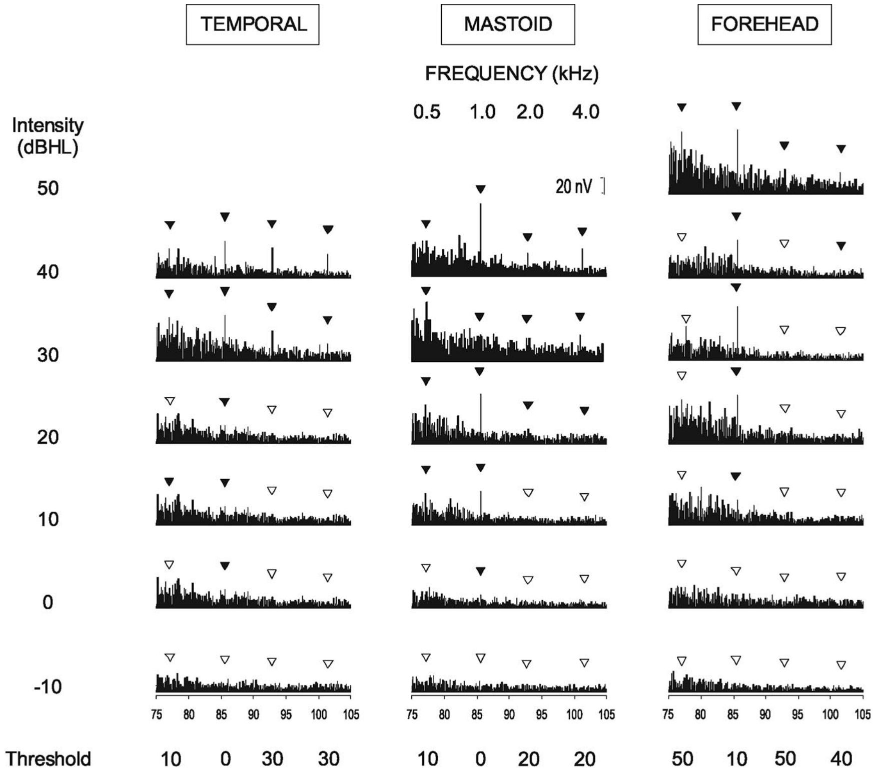

Fig. 3. Representative bone-conduction ASSRs for an individual preterm infant (35 wk PCA) for three bone oscillator placements. Shown are amplitude spectra resulting from FFT analyses (70 to 101 Hz) of the ASSRs. Filled triangles indicate responses that differ significantly ($p < 0.05$) from the background noise. Open triangles indicate no response ($p \geq 0.05$ and EEG noise <11 nV). Threshold is defined as the lowest intensity that produced a significant response.

oscillator placement locations for 13 preterm infants using a 2-way repeated measures ANOVA. For the second analysis of ASSR amplitudes (significant responses only), ASSR amplitudes for 1000 and 4000 Hz and for the three bone-oscillator placement locations were compared for seven preterm infants.

Results

Representative ASSR results to bone-conducted stimuli at the three bone oscillator placements are shown in Figure 3 for a typical preterm infant (35 wk PCA). ASSR thresholds at the temporal bone and mastoid for this infant were the same at 500 and 1000 Hz and only differed by 10 dB at 2000 and 4000 Hz. In contrast, thresholds at the forehead were 10 to 40 dB HL poorer across frequencies compared to the other placements. As shown in Figure 4, there were many fewer significant responses at the forehead compared to the temporal and mastoid placements at the maximum intensity tested for 2000 and 4000 Hz. Table 5 shows mean bone-conduction ASSR thresholds for the preterm infants for three bone-oscillator placement conditions. Mean ASSR thresholds for the temporal bone and mastoid placements were similar, whereas the mean forehead thresholds were elevated compared with the other two placements. The results of an ANOVA revealed a significant effect of placement [F (2,14) = 11.124, p = 0.005, PV = 0.361] and frequency [F (3,21) = 12.328, p = 0.0001, PV = 0.587] but no significant interaction between placement and frequency [F (6,42) = 0.826, p = 0.556, PV = 0.079]. Post hoc comparisons revealed that thresholds for the forehead placement were significantly elevated in comparison to the temporal bone (p = 0.0016) and mastoid (p = 0.003) bone oscillator placements. No significant differences were found for ASSR threshold between the temporal bone and mastoid bone oscillator placements. Consistent with our results reported

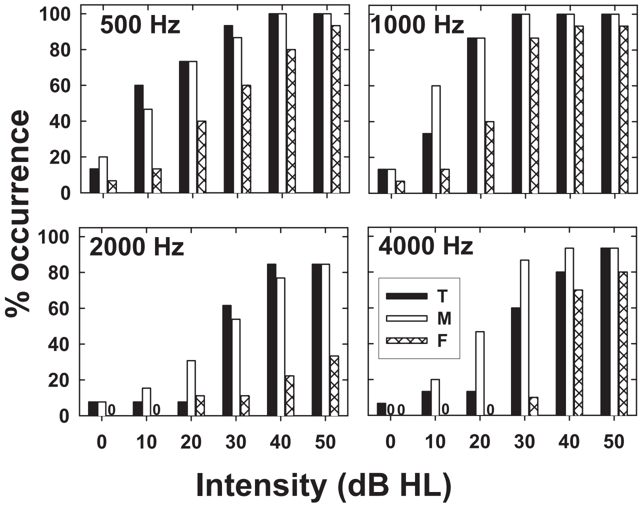

Fig. 4. Cumulative percent occurrence of preterm subjects with significant responses across frequency for temporal (black bars), mastoid (unfilled bars), and forehead (cross-hatched bars) placements (N = 15).

TABLE 5. Bone-conduction auditory steady-state response mean thresholds for 500-, 1000-, 2000-, and 4000-Hz carrier frequencies for three bone-oscillator placements in preterm infants with normal hearing (*N* = 9 to 15)

	Place	500 Hz	1000 Hz	2000 Hz	4000 Hz
Threshold (db HL)	Temporal				
	Mean	16.0	16.7	34.6	33.3
	SD	11.8	9.0	15.1	15.0
	N	15	15	13	15
	Mastoid				
	Mean	17.3	14.0	32.3	26.0
	SD	13.3	9.1	19.6	12.9
	N	15	15	13	15
	Forehead				
	Mean	30.7	26.7	51.1	44.0
	SD	16.2	13.5	13.6	9.7
	N	15	15	9	10

SD, 1 standard deviation.

in a previous study (Small & Stapells, 2006), bone-conduction ASSR thresholds in preterm infants were significantly lower (i.e., better) at 500 and 1000 Hz compared with 2000 and 4000 Hz.

Mean bone-conduction ASSR amplitudes for stimuli presented at 40 dB HL at the three bone vibrator placements are shown in Table 6. Mean ASSR amplitudes obtained when the bone oscillator was placed at the forehead were smaller compared to the other two placements. Results of an ANOVA comparing ASSR amplitude at 40 dB HL revealed a significant effect of placement [F (2,24) = 15.327, p = 0.0001, PV = 0.244]. Post hoc comparisons indicated that amplitudes for the forehead placement were significantly smaller compared with the temporal and mastoid placements; there was no significant difference in mean amplitudes for the temporal and mastoid placements. The main effect of frequency [F (3,36) = 24.524, p = 0.0001, PV = 0.585] was also significant and explained by significantly larger ASSR amplitudes at 500 and 1000 Hz compared with 2000 and 4000 Hz. There was no significant interaction between placement and frequency [F (6,72) = 1.607, p = 0.193, PV = 0.077].

TABLE 6. Bone-conduction auditory steady-state response mean amplitudes at 40 dB HL for 500-, 1000-, 2000-, and 4000-Hz carrier frequencies for three bone-oscillator placements in preterm infants with normal hearing (*N* = 13 to 15).

	Place	500 Hz	1000 Hz	2000 Hz	4000 Hz
Amplitude (nV)	Temporal				
	Mean	47.8	58.2	18.5	17.8
	SD	19.6	24.1	10.2	9.0
	N	13	13	13	13
	Mastoid				
	Mean	48.9	66.0	15.3	21.8
	SD	30.1	32.4	9.3	9.9
	N	15	15	15	15
	Forehead				
	Mean	29.9	41.7	8.7	9.7
	SD	17.6	23.4	4.2	5.6
	N	13	13	13	13

SD, 1 standard deviation.

The above analysis included amplitudes for nonsignificant results because not all of the preterm infants had significant responses at 40 dB HL for all frequencies, particularly at 2000 Hz. A second analysis of the 40 dB HL ASSR amplitude data was thus done to include only significant responses (i.e., not biased to small nonsignificant response amplitudes); ASSR amplitudes for 1000 and 4000 Hz were selected to represent the low and high frequencies, respectively. Mean amplitudes for the forehead placement (31 nV for 1000 Hz, 14 nV for 4000 Hz) remained smaller compared with the temporal (52 nV for 1000 Hz, 22 nV for 4000 Hz) and mastoid (57 nV for 1000 Hz, 26 nV for 4000 Hz) placements. The results of an ANOVA on this smaller data set also revealed a significant effect of placement (p = 0.002, PV = 0.361); post hoc comparisons again indicated that this significant difference was explained by smaller mean ASSR amplitudes for the forehead compared with the other two placements which were not significantly different. There was also no significant interaction between placement and frequency (p = 0.161, PV = 0.071) for this smaller data set.

EXPERIMENT 3: EFFECT OF OCCLUDING THE EAR CANAL ON INFANT ASSRS

The purpose of this experiment was to determine whether the “occlusion effect,” which results in improvement in bone-conduction thresholds at 500 and 1000 Hz in occluded adult ears, is also present for young infants.

Participants and Procedure

Bone-conduction ASSR thresholds were obtained in 12 post-term infants (age range, 1 to 27 wk; mean age, 15 wk) with the ear canal unoccluded and occluded. As described in Experiment 1C, all infants were screened using a DPOAE screening test. By parent report, all infants were normal, healthy babies with no history of middle ear disease.

The bone-oscillator placement location was the same as that used for Experiment 1A. For the unoccluded condition, no insert earphones were placed in either ear canal. For the occluded condition, a pediatric-size insert earphone foam tip was inserted into the ear canal that was on the same side as the bone oscillator. The foam tip was attached to the ER3A tubing that was plugged at the end distal to the ear (i.e., the end of the tubing normally attached to the transducer). Unoccluded ASSR thresholds were always obtained before occluded

ASSR thresholds. The oscillator was hand-held for three of the infants; the elastic-band was used for the remaining nine infants. Multiple ASSR stimuli (500 to 4000 Hz carrier frequencies) were presented in 10-dB steps using a bracketing technique. The starting intensity varied from 10 to 40 dB HL. The lowest level at which a response was present was considered threshold. Bone-conduction ASSR thresholds were compared across frequency and occlusion condition.

Statistical Analyses

A 2-way repeated measures ANOVA was performed to compare ASSR thresholds at 500, 1000, 2000 and 4000 Hz for ears occluded and unoccluded; the same analysis was completed separately for ASSR amplitudes and phase delays at 40 dB HL across frequency and occlusion condition. After case-wise deletion, there were 10, 10 and 7 infants remaining in the analyses of ASSR threshold, amplitude and phase delay, respectively.

Results

Representative ASSR results to bone-conducted stimuli for unoccluded and occluded ears are shown for a typical post-term infant in Figure 5. In this example, occluding the ear canal of this 6-wk-old infant had no effect on bone-conduction ASSR thresholds for 500, 1000, and 2000 Hz, and only a 10-dB increase in ASSR threshold at 4000 Hz. As indicated by the means shown in Table 7, occluding the ear canal had no significant effect on mean bone-conduction ASSR thresholds [$F\ (1,8) = 0.075$, $p = 0.791$, $PV = 0.001$] and there was no significant interaction between frequency and occlusion condition [$F\ (3,24) = 0.530$, $p = 0.666$, $PV = 0.028$]. There was a significant effect of frequency [$F\ (3,24) = 15.770$, $p = 0.0001$, $PV = 0.830$] as expected (Small & Stapells, 2006). Similarly, as shown in Figure 6, mean ASSR amplitudes were not different for the unoccluded and occluded conditions. Results of an ANOVA comparing ASSR amplitudes at 40 dB HL indicated no significant main effect of occlusion condition [$F\ (1,7) = 2.908$, $p = 0.132$, $PV = 0.055$] and no significant interaction between occlusion condition and frequency [$F\ (3,21) = 1.294$, $p = 0.303$, $PV = 0.043$]. There was also no difference in mean ASSR phase delay between occlusion conditions, as shown in Figure 7. Results of an ANOVA comparing ASSR phase delays at 40 dB HL also revealed no significant effect of occlusion condition [$F\ (1,6) = 0.016$, $p = 0.904$, $PV = 0.0002$] and no significant interaction between occlusion condition and frequency [$F\ (3,16) = 0.058$, $p = 0.981$, $PV = 0.003$].

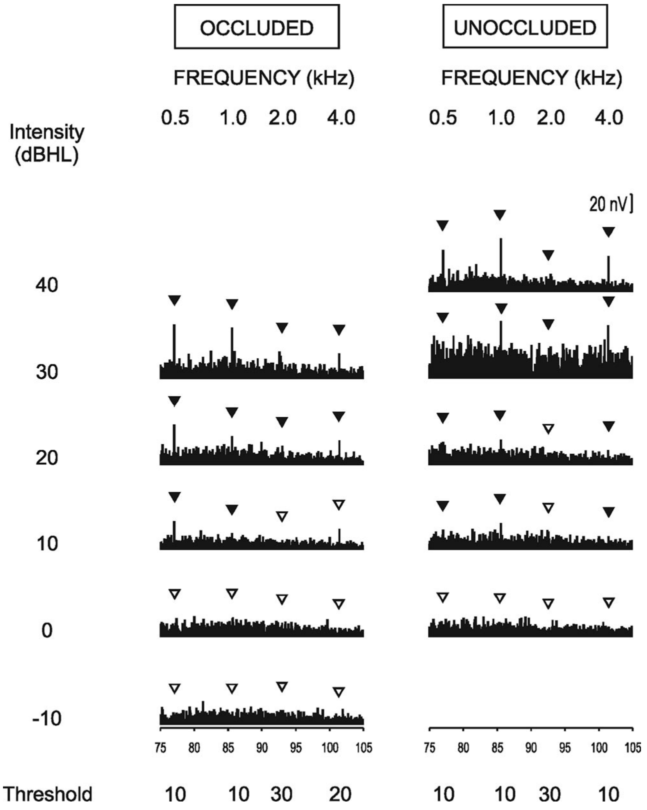

Fig. 5. Representative bone-conduction ASSRs for an individual post-term infant (6 wk) for test ear unoccluded and occluded. Shown are amplitude spectra resulting from FFT analyses (70 to 101 Hz) of the ASSRs. Filled triangles indicate responses that differ significantly ($p < 0.05$) from the background noise. Open triangles indicate no response ($p \geq 0.05$ and EEG noise <11 nV). Threshold is defined as the lowest intensity that produced a significant response.

DISCUSSION

Bone Oscillator Coupling Method

For a number of years, it has been assumed that good clinical practice requires the use of an elastic

TABLE 7. Mean auditory steady-state response thresholds for 500-, 1000-, 2000-, and 4000-Hz bone-conduction carrier frequencies for unoccluded and occluded ears in infants with normal hearing (*N* = 10 to 13; age, 0 to 6 mo)

		500 Hz	1000 Hz	2000 Hz	4000 Hz
Threshold (dB HL)	Unoccluded				
	Mean	18.5	3.1	30.0	16.2
	SD	14.1	8.6	5.8	9.6
	N	13	13	13	13
	Occluded				
	Mean	14.6	3.9	30.0	13.6
	SD	13.9	8.7	13.3	9.2
	N	13	13	10	11
	Difference				
	Mean	3.9	−0.8	1.0	0.9
	SD	11.2	10.4	14.5	8.3
	N	13	13	10	11

Difference, unoccluded minus occluded; SD, 1 standard deviation.

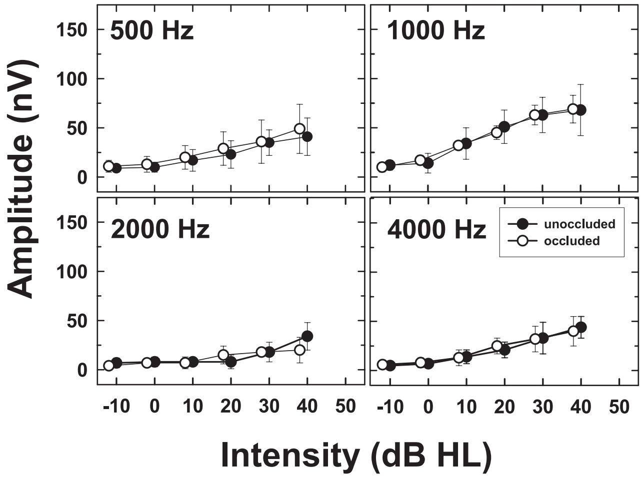

Fig. 6. Mean bone-conduction ASSR amplitudes (±1 SD) across frequency for ears unoccluded (filled circles) and occluded (open circles) for 13 post-term infants

band to couple the bone oscillator to an infant's head when estimating bone-conduction thresholds using auditory-evoked potentials. That is, it has been suggested that it is not appropriate to hold the oscillator in place by hand (Cone-Wesson, 1995; Stapells, 2000; Stapells & Oates, 1997; Yang & Stuart, 2000; Yang et al., 1991). This is the first experiment that has actually compared the force levels applied to the bone oscillator when using the elastic-band and hand-held coupling methods. It is also the first experiment to compare frequency-specific bone-conduction thresholds in infants and adults, using both of these coupling methods.

The results for Experiment 1 showed no significant difference in the mean force applied between coupling methods, although there is some variability in the amount of force applied by individual assistants using each of the coupling methods and a tendency for mean absolute deviations from the target force to be slightly larger for the elastic-band compared to the hand-held method. Notably, threshold variability (i.e., standard deviations) was not greater for the hand-held method. For bone-conduction testing, the main concern is that a consistent amount of force be applied to the oscillator to produce a predictable output of energy at the skull. Yang et al. (1991) measured wave V latencies and amplitudes for bone-conducted click-ABRs using force levels of 225, 325, 425, and 525 g applied using an elastic band to determine the most efficient amount of force to apply to the oscillator. They found that wave V latency decreased significantly when force levels increased from 225 to 325 g but did not change from 325 to 425 g or from 425 to 525 g. They also noted that coupling with a low force level (225 g) caused the oscillator to slip out of the elastic band and that a high force level (525 g) resulted in the elastic band slipping off of the oscillator. Based on their data, Yang et al. concluded that 400 to 450 g was the most efficient amount of force to apply. They further suggested that the practice of holding the oscillator by hand not be encouraged because a constant force could not be applied; they also conjectured that the stimulus output could be dampened using the hand-held method (see Wilber, 1979). They did not investigate either of these assumptions. It is also possible that the frequency response of the bone oscillator could be dampened using an elastic band, although it does seem unlikely that such a dampening effect would be identical for both the elastic-band and the hand-held methods, which would have to be the case as we found no difference in thresholds across frequency for these two methods.

The results of Experiment 1 suggest that individuals can be trained to apply a targeted amount of force to the oscillator by hand to within a reasonable amount of variability (33 g mean absolute deviation) and accuracy (425 ± 100 g for 0% errors produced). It is also noteworthy that when a trained assistant couples the oscillator to the head using an elastic band, without verifying the force level with a spring scale, which is in fact most often the case clinically, the force applied is actually more variable (325 to 600 g) and the accuracy is poorer (425 ± 175 g for 0% errors produced) for the elastic-band coupling compared with the hand-held method. The advantage of the elastic-band method is that you can directly measure the force applied; however, the disadvantage of verifying the force is that it takes extra time and may involve undoing Velcro band several times, which will often wake the baby.

One of the main objectives of this experiment was to determine whether bone-conduction thresholds are affected by coupling method. The adult head is a

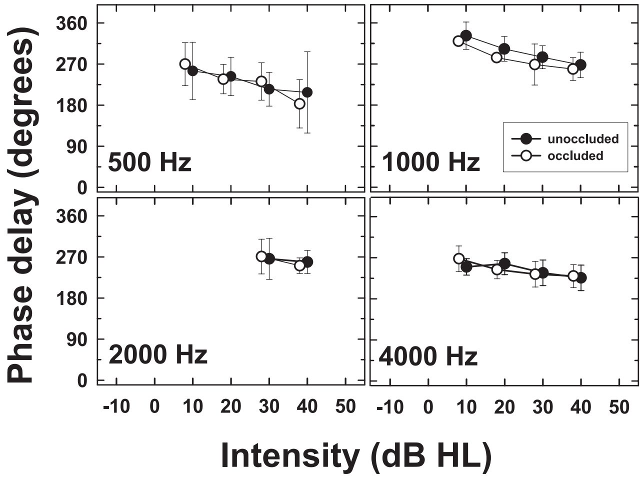

Fig. 7. Mean bone-conduction ASSR phase delays (±1 SD) across frequency for ears unoccluded (filled circles) and occluded (open circles) for 13 post-term infants.

relatively rigid structure with fused sutures so it is assumed that coupling method is the only factor being tested when adult behavioral thresholds to bone-conducted stimuli are compared by using the elastic band and hand-held coupling methods. The bone-conduction behavioral thresholds for adults obtained in this experiment were not significantly different for the two coupling methods (<3 dB difference across frequencies), suggesting that pressing down on the oscillator casing by hand, at least with approximately 425 g of force, does not significantly dampen the response characteristics of the oscillator (Yang et al., 1991). Comparison of bone-conduction ASSRs in young infants obtained using the two different coupling methods indicated an elastic-band versus hand-held mean difference of less than 1 dB. This small difference was not statistically significant. As noted above, ASSR threshold variability was also not different between the two methods. Similarly, the differences in ASSR amplitudes for the two coupling conditions were small (≤10 nV difference) and not statistically significant. The small, albeit nonsignificant, elevation in threshold for the hand-held condition for 4000 Hz may have some practical importance. The infant ASSR threshold and amplitude results for the elastic-band and hand-held coupling conditions are consistent with the adult threshold results which also showed little difference with coupling method.

The only published study that compares bone-conduction thresholds using different coupling methods was conducted in dogs by Munro, Paul & Cox (1997). They compared bone-conduction ABR thresholds to click stimuli in two species of dogs that had significantly different head sizes (Dalmations versus Jack Russell terriers), holding the oscillator both by hand and using a 500-g weight. Similar to our findings, these authors found no difference in bone-conduction thresholds using a hand-held coupling method compared to a method that applies a constant force (i.e., elastic band or 500 g weight).

The clinical implications of these findings are that bone-conduction thresholds can be obtained reliably in infants using either an elastic-band or hand-held coupling method, with the caveat that the individual who is coupling the oscillator to the patient's head must have received appropriate training on whichever method is used. There are clinical situations in which one method may be preferred. For example, the hand-held method may be a better choice if putting the elastic band on the infant's head is likely to wake the infant. There are also clinical settings in which holding the oscillator by hand is not practical, for example, when the evoked potential equipment is outside the sound booth and an assistant is not available to hold the oscillator.

Bone Oscillator Placement

This was the first infant experiment to directly assess the effects of changing oscillator placement on frequency-specific bone-conduction thresholds. The findings from the current experiment suggest that ASSR thresholds obtained with bone oscillator placement on the forehead are substantially elevated with respect to thresholds found with either temporal or mastoid oscillator placements. Thresholds obtained at the temporal and mastoid oscillator placements did not differ significantly. ASSR thresholds for the NICU infants averaged across the temporal and mastoid placements were 17, 15, 34, and 30 dB HL for 500, 1000, 2000, and 4000 Hz, respectively. On average, thresholds for the forehead placement were significantly higher than both the temporal and mastoid placements by at least 14, 11, 18, and 14 dB at 500, 1000, 2000, and 4000 Hz, respectively. These differences may be even greater because absent responses at the maximum intensity were seen more often with the forehead placement compared to the other two placements. Specifically, absent responses at the highest intensity (50 dB HL) were seen for the forehead placement in 18% of the recordings whereas absent responses were seen in only 5% of the mastoid and temporal recordings. This was particularly the case for 2000 and 4000 Hz, in which absent responses were seen for 37% of the forehead placement results compared to only 5% of the temporal and mastoid placement results. The temporal/mastoid placement should therefore be used to maximize the intensity range available to assess thresholds in infants.

The findings that infant thresholds differ between the forehead and mastoid are consistent with previous adult behavioral studies (Dirks, 1994). In adults, forehead thresholds are elevated with respect to mastoid thresholds by an average of 14, 8.5, 11.5, and 8.0 dB for 500, 1000, 2000, and 4000 Hz, respectively (ANSI, 1996). At 500 Hz, infants and adults have the same forehead-mastoid threshold differences. The difference in forehead-mastoid threshold for infants, however, increases with increasing frequency: thresholds at 1000, 2000, and 4000 Hz were larger than those of the adult by 2.5, 6.5, and 6.0 dB, respectively. Possible reasons for the larger attenuation differences at higher frequencies exhibited by the infant compared to the adult may result from the membranous sutures surrounding the temporal bone in the infant (Yang et al., 1987). These membranous sutures have the effect of attenuating the vibratory signal before it reaches the cochlea. When the forehead oscillator placement location is used, the vibratory energy must pass through two layers of membranous sutures before reaching the temporal bone to stimulate the cochlea and thus initiate a physiological response (Yang et al., 1987). Consequently, the effective intensity that reaches the cochlea decreases as the distance between the bone oscillator and the cochlea increases (Stuart et al., 1990). Thresholds obtained at the forehead should, therefore, be worse (i.e., higher) than those obtained at either the temporal/mastoid locations which is consistent with the current findings. As noted by Yang et al. (1987), the membranous sutures in the infant skull may act like a low-pass filter, thus allowing low-frequency energy to pass the sutures with minimal attenuation while the high- frequency energy is substantially attenuated. The idea that membranous sutures act like a low-pass filter in infants may explain why infants and adults have the same attenuation between placements at 500 Hz, but demonstrate more attenuation than adults at 1000, 2000, and 4000 Hz.

In contrast to the findings in the current experiment, Stuart et al. (1990) concluded that changing the position of the oscillator on the temporal bone produced significant differences in signal attenuation to the cochlea. They recorded ABRs to click stimuli at different intensities using different oscillator placements on the temporal bone. They reported differences in ABR latencies for the different temporal placements and suggested that attenuation within the temporal bone occurs in infants because the temporal bone consists of several unfused components, thereby causing a reduction in signal transmission when areas of the temporal bone farther away from the cochlea are used for oscillator placement. They conjectured that oscillator placements which are closest to the cochlea will transmit the greatest intensities, whereas oscillator placements on the unfused areas, further away on the temporal bone, will result in lower intensities (Stuart et al., 1990). Although ABR latency differences existed between the various temporal placements, the assumption that attenuation would follow the same pattern appears to be incorrect. Latency is not linearly related to signal attenuation (e.g., Mackersie & Stapells, 1994; Picton, Stapells & Campbell, 1981), consequently, latency-intensity functions cannot be used to accurately estimate threshold changes (Mackersie & Stapells, 1994). They also did not report wave V amplitudes, which are better predictors of threshold than latency, did not directly estimate threshold at the different placements on the temporal bone, which would have been the best measure for assessing attenuation, and did not use frequency-specific stimuli. The findings of Experiment 2 confirmed that latency data do not accurately estimate attenuation.

Although the results of this experiment show elevated thresholds at the forehead compared to the temporal and mastoid oscillator placements, several limitations exist regarding predicting attenuation of the bone-conducted signal across the skull. One limitation is that ASSR thresholds obtained in preterm infants may not reflect the ASSR thresholds for normal full-term infants for the different oscillator placements. Another limitation is that threshold was not always reached at the maximum test intensity for each placement, particularly at the forehead, resulting in an underestimation of the differences between placements. It is likely that the elevated (i.e., worse) thresholds occur with the forehead location due to greater signal attenuation as a function of distance from the cochlea and, furthermore, the greater differences in threshold at the higher frequencies between the forehead and mastoid in infants are likely due to the low-pass filtering effect imposed by the sutures of the infant skull.

Unoccluded Versus Occluded Ears

It is well established that there are significant infant-adult differences in the transfer of acoustic energy through the outer and middle ear, but these differences are not well understood. We know that the infant ear canal is narrower and shorter than the adult ear (Keefe et al., 1994); it has also been shown that the resonant frequency of the ear canal is higher infants than adults (Keefe et al., 1994; Kruger, 1987; Kruger & Ruben, 1987). We also know that the ear canal wall is thinner and more compliant than in adults up to 2 mo of age (Holte, Margolis & Cavanaugh, 1991). Because we do not fully understand the infant-adult differences in the transfer of acoustic energy in the outer/middle ear, we cannot assume that phenomena such as the occlusion effect, which has only been studied in adults, are necessarily present in infants or, if present, follow the same pattern. This is the first experiment to investigate the occlusion effect in infants. The results of this experiment show that bone-conduction ASSR thresholds in infants younger than 6 mo of age do not change at any of the frequencies tested when the ear canal was occluded. Comparison of unoccluded and occluded bone-conduction mean ASSR thresholds indicated no more than a 4-dB difference across frequency, in contrast to adults whose bone-conduction thresholds at 250 to 1000 Hz improve as much as 17 dB when the ear canal is occluded using an insert earphone (Dean & Martin, 2000). Bone-conduction mean ASSR amplitudes and phase delays were also not significantly affected by occluding the ear canal in these young infants. There are a number of possible explanations for the absence of an occlusion effect in young infants. In adults, the unoccluded ear acts as a high-pass filter [i.e., low-frequency energy is lost through the open ear canal (Gelfand, 1981, p. 66; Tonndorf, 1966)]; in an occluded ear, the improvement in the bone-conduction thresholds is due to the enhancement of the low frequencies. In the infant ear canal, it is possible that there is little increase in low-frequency energy when the ear canal is occluded due to its smaller volume or shorter length (Keefe et al., 1994) or that the insert phone takes up most of the small ear canal volume. Alternatively, if there is low-frequency energy trapped in the occluded infant ear (similar to adults), it may be absorbed by the infant's compliant ear canal wall (Keefe et al., 1993, 1994), resulting in no net increase in energy passing through to stimulate the cochlea.

These preliminary results suggest that there is no effect of occlusion in infants younger than 6 mo of age; however, further studies should be conducted in a larger group of infants to confirm these findings. The clinical implications of these occlusion findings are that it may be possible to do bone-conduction testing, at least in infants younger than 6 mo of age, with ears occluded without applying a correction factor. Also, it is important to investigate whether the occlusion effect is present in older infants and to determine at which age the occlusion effect should be compensated for in clinical testing.

CONCLUSIONS

The results of these experiments have clinical implications for bone-conduction testing procedures used in infants. Our findings support that (i) either the elastic-band or the hand-held method is appropriate for coupling the bone-oscillator to the head, with the important caveat that adequate training has taken place for the method used, (ii) either a temporal or mastoid placement location can be used (forehead placement should be avoided), and (iii) ears may be unoccluded or occluded during bone-conduction testing without significantly affecting threshold estimation.

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Address for correspondence: Dr. David R. Stapells, School of Audiology and Speech Sciences, The University of British Columbia, 5804 Fairview Avenue, Vancouver, BC, Canada V6T 1Z3. E-mail: stapells@audiospeech.ubc.ca.

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