J Am Acad Audiol 5: 379–383 (1994)

Sound Pressure in the External Auditory Canal During Bone-Conduction Testing

Marc Fagelson*
Frederick N. Martin*

Abstract

Sound pressure levels (SPLs) were measured in the external auditory canals (EACs) of 16 subjects with normal hearing and normal middle ear immittance. SPLs were the result of bone-conduction (BC) stimulation at 500, 1000, 2000, and 4000 Hz, with the oscillator placed either on the forehead or on the mastoid process. At 1000, 2000, and 4000 Hz, significantly higher SPLs were measured when the head was stimulated from the mastoid than from the forehead. When SPLs were compared between right and left EACs, forehead placement of the oscillator produced no interaural differences, while mastoid placement resulted in significantly greater EAC SPLs ipsilateral to the oscillator at 2000 and 4000 Hz. We conclude that forehead placement of a BC vibrator may help to lessen the (unwanted) contribution of the EAC to measurements of hearing sensitivity by BC.

Key Words: Bone conduction (BC), external auditory canal (EAC), frontal bone (forehead), mastoid process, oscillator, placement, sound pressure level (SPL)

Two of the most prominent clinical concerns related to bone-conduction (BC) audiometry include the most appropriate site of oscillator placement (e.g., Studebaker, 1962) and the effect of occluding one or both ears, either for masking (e.g., Hood, 1962; Goldstein and Hayes, 1971) or to reduce the effects of acoustic energy radiated from the skull (e.g., Dirks and Malmquist, 1969; Tonndorf, 1972; Frank and Holmes, 1981; Silman and Silverman, 1991). Studebaker (1962) identified the frontal bone as the optimum location on which to place the BC vibrator because it decreases intersubject and intrasubject variability. He reported that forehead behavioral responses were more consistent representations of the cochlea's sensitivity than those obtained with mastoid process placement.

Relatively few data regarding sound energy in the external auditory canal (EAC) have been collected from human listeners. Tonndorf (1966, 1971, 1972) measured EAC sound pressure levels (SPLs) and reported that middle ear status and the resonant frequency of the individual middle ear affect responses to BC stimuli. These thresholds were measured by monitoring the cochlear microphonic and they changed as middle ear structures were altered; the greatest shift in BC thresholds occurred at the resonant frequency of a given species' middle ear system. Tonndorf's results corroborated the Carhart (1950) observation that stapes fixation in humans, associated with otosclerosis, alters the BC response most at about 1800 Hz, which is typically the conductive system's resonant frequency in humans. As a consequence, the "Carhart notch" is most often observed clinically at 2000 Hz.

Clinical and experimental data provided by several investigators indicate the effect that oscillator placement exerts on BC test results. Studebaker (1962) ascribed the improved test–retest reliability with frontal bone placement to the larger, more homogeneous surface offered by the forehead, as well as its lack of pneumatization relative to the mastoid. Dirks and Malmquist (1969) and Tonndorf (1972) showed that the middle ear inertial component decreases when the skull is vibrated from the

*Program in Communication Sciences and Disorders, The University of Texas at Austin, Austin, Texas

Reprint requests: Frederick N. Martin, Program in Communication Sciences and Disorders, The University of Texas at Austin, Austin, TX 78712-1089

frontal bone, a finding that helps to explain the greater acceleration required at that location to reach a subject's BC threshold (ANSI, 1981).

Apparently, the middle ear contributes less to the BC response when the skull is vibrated along a different plane than that occupied by the ossicles. Consider the ossicular chain, particularly the malleus and incus, as analogous to a pendulum with one preferred plane of motion (similar to that of a grandfather clock) (Tonndorf, 1972). When the temporal bone is stimulated via BC, the malleus and incus are vibrated in the same direction that the ossicles naturally conduct sound, similar to the pendulum's back-and-forth motion. But if the same force is applied orthogonally, from the frontal bone, the transfer of energy from middle to inner ear is far smaller, similar to the reduced excursion displayed by a pendulum when pushed from the front, rather than from the side.

The current study investigates placement of the BC vibrator and its effect on the SPL measured in both EACs across four stimulus frequencies. We questioned whether SPLs in the EAC are the same when the skull is distorted with forehead oscillator placement, as it is when the vibrator is placed on the mastoid process. Because the BC-stimulated skull vibrates in a uniform manner, the SPLs present in each EAC should be identical during BC stimulation.

METHOD

Subjects

Sixteen female graduate students in audiology volunteered to take part in the experiment. We did not consider it necessary to control for gender effects, considering the relative nature of the data collected and the fact that no voluntary responses were required of any of the subjects. EACs were inspected otoscopically before testing began to ascertain that they were free of interfering cerumen or other debris. Subjects presented with normal middle ear function bilaterally (see Van Camp et al, 1986) immediately prior to their participation in the study when tested with a GSI 33 acoustic immittance meter. Normal middle ear function was defined as a tympanogram with a single peak, at which the tympanic membrane (TM) displayed maximum displacement with external ear pressures between –50 and +50 daPa. Maximum TM displacement for all subjects was between 0.4 and 0.8 mL. Subjects were required to exhibit normal middle ear function to reduce variability associated with the ossicular effects described above.

Stimuli

Pure tones were delivered via a Radioear B-71 BC vibrator at 500, 1000, 2000, and 4000 Hz. Test stimuli were generated by a Beltone 10-D audiometer on which calibration to ANSI (1989) standards was checked prior to each data collection session with respect to output, frequency, and attenuator linearity. A Brüel & Kjaer (model #493C) artificial mastoid connected to a Brüel & Kjaer sound level meter (model #2203) and octave filter set (model #1613) were used to check calibration. Signal intensities were 40, 50, and 60 dB HL (ANSI, 1989). These levels were chosen so that the EAC SPLs were well above the noise floor of the test suite.

Procedure

All measurements were made in a commercial sound-treated booth that met ANSI (1977) standards for ambient noise levels in audiometric workspaces using a Fonix FP40 probe microphone and portable test box. The BC vibrator was placed alternately on the frontal bone (forehead) and right mastoid process for all subjects. The right mastoid was selected arbitrarily since the goal was to make SPL measurements in both EACs. The probe microphone was placed in each EAC in turn during mastoid and forehead stimulation (Table 1). A site at or beyond the osseo-cartilaginous junction served as a landmark for microphone placement across subjects. Proximity of the probe microphone to the TM was a priority, as it has been reported (Dirks and Kincaid, 1987; Tecca, 1990) that measurement error is smallest when the microphone is proximal to the TM. The order in which measurements were made was counterbalanced.

Table 1 Order in which Measurements Were Taken

Probe Microphone	*BC Vibrator*
Left EAC	Right mastoid
Left EAC	Forehead
Right EAC	Forehead
Right EAC	Right mastoid

EAC = external auditory canal; BC = bone conduction.

RESULTS

Linear increases in SPLs measured in subjects' EACs coincided with the 10-dB step size used in all frequency and placement conditions (from 40 to 60 dB HL). The mean difference in SPL measured across all subjects, placements, and frequencies with a 10-dB change in presentation level was 10.04 dB (SD = 0.30 dB). The data analysis was based only on the SPL values achieved with an input of 50 dB HL because the data obtained at 40 and 60 dB HL merely demonstrated that the effects were linear. Data were analyzed to determine whether any differences existed between right external auditory canal (REAC) and left external auditory canal (LEAC) SPLs depending on vibrator placement and frequency.

Mastoid versus Forehead EAC SPLs

Tables 2 and 3 reveal that the mean SPLs present in the EACs and standard deviations are lower when skull displacement occurs with forehead vibrator placement than when the vibrator is placed on the mastoid. This difference is more pronounced in the higher frequencies and is greatest at 2000 Hz. A comparison between REAC and LEAC SPLs appears in Figure 1. Note that significant interaural differences were present only with mastoid placement at 2000 and 4000 Hz.

Table 2 Means, Ranges, and Standard Deviations of SPLs in the Right External Auditory Canal

	Mastoid	*Forehead*	*Difference*
500 Hz			
Mean	62.61	60.04	2.57
SD	6.44	4.74	
Range	53.8–72.5	52.9–70.8	
1000 Hz			
Mean	71.36	63.70	7.66
SD	3.45	4.32	
Range	65.4–78.2	57.0–70.9	
2000 Hz			
Mean	70.14	55.51	14.63
SD	5.23	7.23	
Range	60.8–78.5	39.3–65.7	
4000 Hz			
Mean	72.33	59.98	12.35
SD	4.71	4.86	
Range	65.8–83.3	49.4–67.1	

With the bone-conduction oscillator placed on the right mastoid and the forehead with an input of 50 dB HL.

Table 3 Means, Ranges, and Standard Deviations of SPLs in the Left External Auditory Canal

	Mastoid	*Forehead*	*Difference*
500 Hz			
Mean	62.03	59.28	2.75
SD	6.39	4.80	
Range	52.9–75.0	52.8–68.4	
1000 Hz			
Mean	71.22	63.18	8.04
SD	3.30	5.67	
Range	65.4–77.2	50.0–70.4	
2000 Hz			
Mean	61.39	56.89	4.50
SD	3.18	7.77	
Range	57.4–65.7	43.8–72.0	
4000 Hz			
Mean	53.49	57.66	4.17
SD	4.13	4.22	
Range	43.4–58.5	49.7–63.3	

With the bone-conduction oscillator placed on the right mastoid and the forehead with an input of 50 dB HL.

A two-factor, repeated measures ANOVA was conducted on the differences between the EAC SPLs (Table 4). Both frequency and placement effects were significant. More compelling than the main effect findings, however, was the frequency by placement interaction, which also reached significance. The significant interaction effect reduced the importance of main effect findings because it indicated that significant variation due to one factor, such as oscillator placement, depended upon the effect of stimulus frequency. To determine the significant interactions, Tukey's HSD post-hoc test was conducted and indicated that mastoid placement

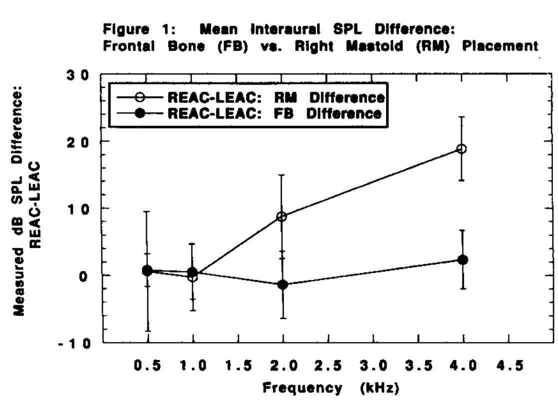

Figure 1 Comparison between REAC and LEAC SPLs.

Table 4 Source Table of REAC-LEAC SPL Differences

Source	*df*	*MS*	*F*	*p*
Subjects	15	46.85		
Placement	1	1,346.15	52.48	<.001
Frequency	3	2,189.01	27.15	<.001
Placement × Frequency	3	1,660.75	21.08	<.001
Placement × Subject	15	25.66		
Frequency × Subject	45	26.87		
Placement × Subject × Frequency	45	26.26		

REAC = right external auditory canal; LEAC = left external auditory canal.

resulted in significant REAC-LEAC differences at 2000 and 4000 Hz. No significant differences were noted between EAC SPLs with frontal bone stimulation.

DISCUSSION

As the cochlea is distorted in proportion to the distortion of the walls of the EAC (Tonndorf, 1972), EAC SPLs should be consistent to some degree with behavioral thresholds. We can conclude, therefore, that the greater vibrator force required to obtain thresholds from the forehead are due, in part, to the lower SPLs in the EAC. Stated differently, the osseotympanic contribution to hearing by bone conduction is smaller when forehead placement is used than when the mastoid is the test site. Since the difference in EAC SPL was shown to be linear, this effect should be operational at all intensities.

Other effects of oscillator placement were revealed when the differences between REAC and LEAC SPLs were compared across frequency. With frontal bone stimulation, no significant differences between the SPLs present in two EACs were measured. When the right mastoid was stimulated, however, significantly greater SPLs were present in the REAC at 2000 and 4000 Hz. The lack of interaural differences at 500 and 1000 Hz indicated that proximity of the vibrator to the probe microphone was not the sole cause of the interaural differences. Rather, the higher frequency signals may have been radiated into the air and the EAC from the BC vibrator (Frank and Holmes, 1981; Silman and Silverman, 1991). At 2000 and 4000 Hz, more energy would be attenuated from the contralateral ear by the head than at lower frequencies, resulting in large interaural SPL differences. Silman and Silverman (1991) suggested that when excessive radiated energy is suspected, such as in the case of a high-frequency air-bone gap with no middle ear dysfunction, an earplug can be placed in the test ear to reduce the amount of air-conducted sound from the BC vibrator.

Our findings help to explain the observation that mastoid process placement results in greater intersubject variability than does forehead placement (e.g., Studebaker, 1962). Apparently, many of the confounding elements associated with BC testing, such as the undesirable contributions of the conductive system and airborne acoustic energy, are reduced with frontal bone placement. Therefore, care should be exercised when interpreting results obtained with mastoid placement, particularly if a high-frequency conductive hearing loss is indicated.

Apparently, most audiologists mask during BC testing when an air-bone gap appears in the test ear (Martin et al, 1994). Although it can never be known for certain which ear is responding during a BC test unless proper masking is used, the point becomes moot when there is no air-bone gap because the diagnosis will be either normal hearing or sensorineural hearing loss, depending on the air-conduction threshold. Many clinicians do not bother to test BC from both mastoids when bilaterally symmetrical losses appear with no air-bone gap based on results of the first mastoid tested. The appearance of an audiogram with symbols indicating that only one ear has been tested by BC may cause confusion. The use of a forehead BC symbol simply shows that bone conduction has been tested and that no air-bone gap exists in either ear. Naturally, if an air-bone gap is found, contralateral masking is indicated to ascertain the sensorineural sensitivity in each ear.

Since pure-tone audiometry remains the basic hearing test, BC, with all of its attendant problems, must be considered to be an important, albeit often problematic, measurement. We submit that clinicians should be prepared and audiometers calibrated to test BC using both frontal bone and mastoid placements. Granted, the equipment's limits will be reached at lower HLs during frontal bone stimulation, so for those cases where no response to forehead BC measurements are obtained at the limits of the equipment and a profound mixed hearing loss is a possibility, the clinician can test from the mastoid, increasing the equipment's range by about 10 dB. However, in most cases, stimulating from the frontal bone will provide a more reliable and accurate representation of the cochlear reserve than BC stimuli delivered to the mastoid process. This study adds to the growing body of evidence that the forehead is the preferred placement site for BC testing. We urge clinicians to consider this in determining the protocols for their basic hearing evaluations.

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