Quantifying Air-Conducted Acoustic Radiation from the Bone-Conduction Vibrator

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Abstract

Sound pressure levels in the external auditory canals of 50 subjects were measured at 2000 and 4000 Hz with a bone-conduction vibrator on the forehead, the mastoid ipsilateral to the probe microphone, and the mastoid contralateral to the probe microphone. A plug was placed in the external auditory canal to minimize sound pressure levels in the external auditory canal produced by the osseotympanic mode of bone conduction. Results suggest that clinically significant false air–bone gaps (greater than 10 dB) due to acoustic radiation into the concha from the bone-conduction vibrator are most likely to occur at 4000 Hz when the bone-conduction vibrator is placed on the mastoid of the test ear. To minimize the possible confounding effects of acoustic radiation, the bone-conduction vibrator may be placed on the forehead or the mastoid contralateral to the test ear while masking the nontest ear.

Key Words: Acoustic radiation, air-bone gap, bone conduction, mastoid process

Abbreviations: B&K = Brüel and Kjær; EAC = external auditory canal

A clinical concern related to bone-conduction (BC) audiometry is the effect of acoustic energy radiating from the BC vibrator via air conduction (AC) into the external auditory canal (EAC). This AC signal may be intense enough to serve as an additional cue to patients during behavioral threshold testing that should be by BC alone. The patients' BC thresholds would thus be misrepresented as better than they actually are if the patients are responding to the additional, radiated AC signal at a lower level than their true BC threshold. In these cases, invalid air–bone gaps have been observed, especially in the higher frequencies (Dirks and Malmquist, 1969; Tonndorf, 1972; Frank and Holmes, 1981; Silman and Silverman, 1991). Previous studies have indicated that excessive acoustic radiation occurs primarily at 4000 Hz (Bell et al, 1980; Shipton et al, 1980; Frank and Holmes, 1981; Fagelson and Martin, 1994).

In an attempt to avoid the possibility of BC vibrators radiating air-conducted sounds, the vibrators were redesigned, resized, and recased (ANSI, 1972). Results from subsequent psychoacoustic (Bell et al, 1980) and physical (Frank and Richards, 1979; Bell et al, 1980; Shipton et al, 1980; Frank and Holmes, 1981; Fagelson and Martin, 1994) measurements confirmed the presence of acoustic radiation at 2000 and 4000 Hz from the most commonly used types of vibrators. Therefore, unable to eliminate acoustic radiation by altering the design or make-up of the BC vibrators, researchers attempted to quantify the exact amount of acoustic radiation produced.

Frank and Richards (1979) and Shipton et al (1980) measured acoustic radiation at different frequencies produced by Radioear B-71, B-72, and B-70A BC vibrators placed on an artificial mastoid. Bell et al (1980), Shipton et al (1980), and Frank and Holmes (1981) measured acoustic radiation at the entrance of the human EAC produced by Radioear BC vibrators placed on the mastoid. All of these studies showed that the maximum acoustic radiation occurred at 4000 Hz, especially when using the Radioear B-71 and B-72 vibrators.
Fagelson and Martin (1994) measured the sound pressure levels in EACs with a probe-tube microphone. They were interested in the effects of B-71 vibrator placement (mastoid ipsilateral to a probe microphone vs forehead) on the amount of acoustic energy in the EAC. Results indicated that the mean SPLs present in the EAC were high enough to produce an AC response for both placements but were significantly lower during BC stimulation from the forehead, especially at 2000 and 4000 Hz.

Researchers (Frank and Richards, 1979; Bell et al, 1980; Shipton et al, 1980; Frank and Holmes, 1981; Fagelson and Martin, 1994) attempted to quantify the SPLs in the EAC during BC testing at different frequencies and with different sites of stimulation. However, their methods did not provide a means of separating energy entering the EAC via the concha from energy actually generated within the EAC due to the various effects of vibrating the skull (Tondorf, 1972). Thus, the amount of airborne acoustic radiation measured in the EAC during the previous studies may have been confounded.

The purpose of this study was threefold: (1) to systematically quantify the amount of acoustic radiation present in the EAC that is produced by the BC vibrator alone; (2) to evaluate the effects of two different frequencies (2000 and 4000 Hz) on the amount of airborne acoustic energy radiated into the EAC during BC testing; and (3) to determine the effects of different placements of the vibrator on the amount of acoustic energy radiated into the EAC.

**METHOD**

**Subjects**

Fifty (3 male, 47 female) adults participated in the experiment (mean age: 24 years; range: 19–42 years). Otoscopy and tympanometry were performed bilaterally before testing to ensure that the EACs were free of obstruction and that the middle ears were functioning normally. Normal middle-ear function was defined as a tympanogram with a single peak at which the tympanic membrane displayed maximum displacement with external ear pressures between -50 and +50 daPa. Normal hearing sensitivity was not required as it would have no influence on the results of the physiologic measures carried out in this study.

**Stimuli**

Air-conducted pure tones were delivered through TDH-50 earphones. Bone-conducted pure tones were presented via a Radioear B-71 vibrator at 2000 and 4000 Hz. All test stimuli were generated by a Grason-Stadler (GSI-16) audiometer, which was calibrated to ANSI (1996) standards. A Brüel & Kjaer (B&K) sound level meter (model #2203) and octave filter set (model #1613) were used for AC calibration. A B&K artificial mastoid (model #493C) connected to the B&K sound level meter and octave filter set were used for calibration of the BC vibrator. Appropriate force values were applied (per ANSI 1992 standards) for both forehead and mastoid BC output at 2000 and 4000 Hz. Each signal was presented at 65 dB HL because it is the most intense BC signal that a conventional audiometer can produce at 4000 Hz. Therefore, it would be the most likely to cause acoustic radiation in the EAC that is measurable above the noise floor of the test suite. Further, Fagelson and Martin (1994) demonstrated a linear decrease in acoustic radiation from the BC vibrator that coincided with the decrease in stimulus intensity. Thus, the largest amount of acoustic radiation will be produced by the most intense BC signal.

**Procedure**

Subjects were seated in a sound-treated booth that met ANSI (1991) standards for acceptable ambient noise levels, and AC thresholds were measured at 2000 and 4000 Hz. Then, one half of an EAR plug, attached to a strong string, was placed into the EAC with the lateral surface at the osseocartilagenous junction to eliminate SPL in the EAC produced by the osseotympanic mode of BC. Thus, any remaining SPL measured in the EAC could be attributed to acoustic radiation from the BC vibrator itself. Thresholds were remeasured to determine the amount of attenuation provided by the plug. Next, a tube connected to a Fonix (FP40) probe microphone was placed in either the right or left EAC, just lateral to the plug, where it was taped securely in place for the duration of the experiment (Fig. 1). The probe microphone was attached to a portable test box and was used to measure the SPL in the EAC. The BC vibrator was placed on the forehead, a 2000-Hz tone at 65 dB HL was presented, and the SPL in the EAC was measured. At this same placement, the SPL in the
One half of an EAR plug was placed at the osseocartilagenous junction. A tube connected to the probe microphone was secured just lateral to the plug and was used to measure the SPL in the EAC.

EAC was measured for a 4000-Hz tone with a 65 dB HL input. Then, this process was repeated with the BC vibrator on the mastoid ipsilateral to the probe microphone and the mastoid contralateral to the probe microphone. Presentation orders of stimulus frequency and BC vibrator placements were counterbalanced across subjects to minimize order effects.

**RESULTS**

**Parceling of the SPL Measured in the EAC**

AC thresholds were shifted, by virtue of the ear plug, an average of 34.7 dB (range: 20-50 dB) at 2000 Hz and 36.6 dB (range: 25-55 dB) at 4000 Hz. This suggests that any energy radiating into the EAC associated with vibration of the skull during BC testing (Tonndorf, 1972) would be sufficiently attenuated by the plug. This occlusion successfully eliminates outward radiation so that the SPLs measured in the EAC (lateral to the plug) can be attributed to acoustic energy radiated from the BC vibrator into the EAC via the concha.

**Quantifying the Amount of AC Acoustic Radiation Produced by the BC Vibrator**

Table 1 reveals the mean SPLs measured in the EACs of the 50 subjects. A decision was made regarding whether the acoustic radiation was sufficient to cause a false air–bone gap. This decision was dependent upon the relationship between the SPL that should be generated in the EAC by an AC receiver at 65 dB HL and the SPL radiating into the EAC by a BC vibrator driven at that same hearing level. This can be expressed as the formula A > B, where "A" represents the SPL in the EAC radiated from the BC vibrator at 65 dB HL and "B" represents the SPL in the EAC resulting from presentation of an AC signal through earphones at the same level (65 dB HL). According to ANSI (1996), 76 dB SPL and 75.5 dB SPL, respectively, would be required to produce 2000-Hz and 4000-Hz AC pure tones at 65 dB HL as measured in a 6-cc coupler. Thus, "B" equals 76 dB SPL at 2000 Hz and 75.5 dB SPL at 4000 Hz. While excessive acoustic radiation is indicated by A > B, when A = B and A < B, acoustic radiation should not be considered a clinical problem (Table 2).

**Table 2 Example Decisions Regarding Excessive Acoustic Radiation from a Bone-Conduction Vibrator**

<table>
<thead>
<tr>
<th>SPL in the EAC from the BC Vibrator (A)</th>
<th>SPL in the EAC from Earphones (B)</th>
<th>Formula</th>
<th>Problem?</th>
</tr>
</thead>
<tbody>
<tr>
<td>90.73</td>
<td>75.5</td>
<td>A &gt; B</td>
<td>Yes</td>
</tr>
<tr>
<td>69.27</td>
<td>75.5</td>
<td>A &lt; B</td>
<td>No</td>
</tr>
<tr>
<td>75.50</td>
<td>75.5</td>
<td>A = B</td>
<td>No</td>
</tr>
</tbody>
</table>

A 65 dB HL, 4000-Hz tone was introduced with the BC vibrator placed on the mastoid ipsilateral to the probe microphone, and on the forehead.

*With a 2000-Hz tone at 65 dB HL, some SPL measurements were too small to be made with certainty due to the interference of the noise floor.
Excessive Acoustic Radiation

Using the formula $A > B$, individual and mean data (see Table 1) reveal almost no excessive acoustic radiation, in any BC vibrator placement, when BC stimulation was at 2000 Hz. (There was one exception with the BC vibrator on the mastoid ipsilateral to the probe microphone.) In all but one case, the SPL in the EAC radiated from the BC vibrator ($A$) was less than the expected SPL in the EAC resulting from an AC signal through earphones ($B$). Single-group design, paired t-tests indicated that at 2000 Hz, for each BC vibrator placement, $A < B$ is significant (Table 3).

At 4000 Hz, however, in 48 of 50 subjects SPLs in the EAC radiated from the BC vibrator ($A$) were greater than the expected SPLs in the EAC resulting from an AC signal through earphones ($B$) with two placements, the mastoid ipsilateral to the probe microphone and the forehead. Using the third placement (mastoid contralateral to the probe microphone), only one subject had SPLs in the EAC radiated from the BC vibrator ($A$) greater than the SPL in the EAC from AC stimulation via earphones ($B$). Paired t-tests indicated that $A > B$ is significant for placement on the forehead and for the mastoid ipsilateral to the probe microphone. $A < B$ is significant for placement on the mastoid contralateral to the probe microphone (see Table 3).

A two-factor analysis of variance (ANOVA) with repeated measures on the main effects of frequency (two levels) and vibrator placement (three levels) was performed to determine whether significant differences exist (Table 4). The results of the ANOVA indicated that both the main effects of frequency ($p = .0001$) and vibrator placement ($p = .0001$) are significant, as is the interaction ($p = .0001$). It should be noted that only subjects with a data entry at all three placements for each frequency of stimulation were considered in the analysis. This reduced the number of subjects included in the analysis, since with the 2000-Hz tone only, the acoustic radiation was often not sufficient at one or more placements of the BC vibrator to be measurable above the noise floor in the EAC of some subjects. This reduced number of subjects did not confound the statistical significance of this study and, in fact, strengthened the findings that excessive acoustic radiation in the EAC is not a problem at 2000 Hz.

Figure 2 illustrates the relationship between the BC vibrator placement and the frequency of stimulation and shows the significant interaction. Stimulation with a 4000-Hz tone produced a significantly greater amount of acoustic radiation at all three placements versus stimulation with a 2000-Hz tone. Further, using a 2000-Hz tone, the amount of acoustic radiation found at all three placements of the BC vibrator is virtually the same (within 1 dB). However, using a 4000-Hz tone, the amount of acoustic radiation at each of the three placements of the BC vibrator appears markedly different. Thus, when completing a post-hoc analysis to determine which of the three vibrator placements was responsible for the significant differences seen in the main effect of placement, although all data for both frequencies were included, it appears that it was primarily the data at 4000 Hz that contributed to these differences in placement.

Effects of BC Vibrator Placement

Results of a post-hoc analysis using Scheffe's test for the main effect of placement showed that the amount of acoustic radiation is significantly greater (at an alpha level of .05) when
Table 4  Two-Factor ANOVA with Repeated Measures Source Table of SPL Differences in the EAC due to Frequency and Radioear B-71 BC Vibrator Placement

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject</td>
<td>13</td>
<td>526.82</td>
<td>40.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>1</td>
<td>8863.55</td>
<td>8863.55</td>
<td>577.22</td>
<td>.0001*</td>
</tr>
<tr>
<td>Frequency x subject</td>
<td>13</td>
<td>201.88</td>
<td>15.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Placement</td>
<td>2</td>
<td>1793.09</td>
<td>896.55</td>
<td>64.25</td>
<td>.0001*</td>
</tr>
<tr>
<td>Placement x subject</td>
<td>26</td>
<td>362.79</td>
<td>13.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency x placement</td>
<td>2</td>
<td>1238.81</td>
<td>619.40</td>
<td>51.38</td>
<td>.0001*</td>
</tr>
<tr>
<td>Frequency x placement x subject</td>
<td>26</td>
<td>313.42</td>
<td>12.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The N, and therefore df, was decreased to 14 because only 14 subjects had SPLs in the EAC measurable above the noise floor at 2000 Hz. At 4000 Hz in all cases, SPLs were measurable well above the noise floor.

*An alpha level of .05 was chosen to indicate significance.

stimulating (1) the mastoid ipsilateral to the probe microphone versus the mastoid contralateral to the probe microphone and (2) the forehead versus the mastoid contralateral to the probe microphone. No significant difference was found between the amount of acoustic radiation in the EAC with the BC vibrator placed on the mastoid ipsilateral to the probe microphone versus the forehead.

For the remainder of this paper, the effects of the placement of the BC vibrator are only discussed for BC stimulation at 4000 Hz because there was no significant acoustic radiation at 2000 Hz, for any subject, for any placement. In 34 of 50 subjects, when the BC vibrator was placed on the mastoid ipsilateral to the probe microphone, the SPLs in the EAC were greater than the SPLs recorded in the EAC when the BC vibrator was placed on the forehead (mean difference: 4.9 dB; range: 0.3–16.2 dB). In 16 of 50 subjects, the SPLs in the EAC were greater when the BC vibrator was on the forehead than when the BC vibrator was placed on the mastoid ipsilateral to the probe microphone (mean difference: 3.2 dB; range: 0.4–11.9 dB). In all cases, SPLs in the EAC were greater from the forehead than the mastoid contralateral to the probe microphone (mean difference: 15.0 dB; range: 2.6–30 dB). Also, in all cases, SPLs in the EAC were greater from the mastoid ipsilateral to the probe microphone versus the mastoid contralateral to the probe microphone (mean difference: 17.4 dB; range: 2.4–32.7 dB).

**DISCUSSION**

This study indicates that from a clinical perspective, excessive acoustic radiation from the Radioear B-71 BC vibrator may be a concern only at 4000 Hz. The largest amount of acoustic radiation occurred when the BC vibrator was placed on the mastoid ipsilateral to the test ear, with the forehead placement producing the next largest amount. Acoustic radiation is statistically significant for both placement on the forehead and mastoid ipsilateral to the test ear. Another question, however, is whether an air–bone gap resulting from acoustic radiation from a BC vibrator is clinically significant. Most audiologists consider an air–bone gap of 15 dB or greater to indicate a clinically significant conductive hearing loss (Martin et al, 1998). This means that SPL in the EAC radiated from the BC vibrator (A) must be at least 15 dB greater than the expected SPL in the EAC resulting from an AC signal through earphones at the same hearing level (B) in order to produce a false air–bone gap of clinical concern.
Using a 4000-Hz stimulus at 65 dB HL, the SPL in the EAC produced by BC stimulation (A) must be 15 dB greater than 75.5 dB SPL (the resulting SPL in the EAC from AC stimulation via earphones, B). When the BC vibrator was placed on the mastoid ipsilateral to the probe microphone, 18 percent of subjects demonstrated excessive acoustic radiation (mean “A” = 90.9 dB SPL). Only one subject had excessive acoustic radiation (“A” = 90.3 dB) with the vibrator placed on the forehead. There was no excessive acoustic radiation measured in any EAC when the BC vibrator was placed on the mastoid contralateral to the probe microphone. The low percentages in this study, at all three placements, suggest that clinically, excessive acoustic radiation from the BC vibrator, at 4000 Hz and 65 dB HL, should not be a widespread problem. In fact, it appears to be an extremely rare occurrence when testing from the forehead, and no problem at all when testing from the mastoid contralateral to the test ear. The findings of this study combined with those of Fagelson and Martin (1994) also imply that excessive acoustic radiation from the BC vibrator will not be present when using a BC stimulus intensity lower than 65 dB HL. Fagelson and Martin (1994) demonstrated a linear relationship between acoustic radiation and stimulus intensity. In the present study, excessive acoustic radiation was rare when using a 65 dB HL BC signal, and thus is not likely to be found at lower levels of stimulation.

This does not suggest that false air–bone gaps do not occur due to excessive acoustic radiation from the BC vibrator. It appears, however, that the contribution of acoustic radiation from the Radioear B-71 BC vibrator to the false air–bone gap is minimal, and that other sources must be considered. It has been shown that there are many technical problems in the comparison of AC and BC thresholds. First, the standardizations of normal-hearing threshold calibration for AC and BC arise from unrelated experiments on different groups of subjects. Also, in the case of BC, such critical issues as vibrator placement are not well agreed upon (Shipton et al, 1980; Fagelson and Martin, 1994), and results tend to have poorer test–retest reliability. This variability can be due to a number of influences, such as the various effects of skull vibration, middle-ear status, the resonant frequency of the middle ear (Tonndorf, 1972), and the site of vibrator placement (Dirks and Malmquist, 1969; Tonndorf, 1972; Fagelson and Martin, 1994). However, it has been shown experimentally that when the BC vibrator is placed on the forehead, the confounding effects of these variables is minimized, and more reliable and accurate results are obtained than those obtained when the BC vibrator is placed on the mastoid (Dirks and Malmquist, 1969; Tonndorf, 1972; Fagelson and Martin, 1994).

The fact that forehead placement of the BC vibrator minimizes various effects of skull vibration, middle-ear status, and resonant frequency of the middle ear on BC measurements (Dirks and Malmquist, 1969; Tonndorf, 1972; Fagelson and Martin, 1994) and the rare occurrence of excessive acoustic radiation seen in the present study suggest that many of the contributions to false air–bone gaps can be eliminated when testing BC from the forehead. However, if mastoid placement must be used, assuming interaural attenuation to be 0 dB, the non-test ear may be masked, and the BC vibrator may be placed on the mastoid contralateral to the test ear. This would best minimize the effects of acoustic radiation from the BC vibrator into the EAC of the test ear.

Future research on the effects of different types of BC vibrators on the amount of acoustic radiation in the EAC may be warranted. In this study, the Radioear B-71 BC vibrator was the only one used because it is the only one with ANSI standards (ANSI, 1972). Different results would probably be found with other BC vibrators. For example, Bell et al (1980), Frank and Richards (1980), and Frank and Holmes (1981) measured the most acoustic radiation, at most frequencies, when stimulating with the Radioear B-72 BC vibrator. These results, in combination with ours, imply an even greater occurrence of false air–bone gaps with the B-72 BC vibrator versus the B-71 BC vibrator, and clinicians should be aware of this possibility.

Further, gender (male vs female) and age (adult vs child) differences in ear canal volume or skull impedance could affect the amount of acoustic radiation found in the ear canal. In this study, only adults, and primarily females, were available to be examined. However, the lack of evidence in the literature on gender effects of skull impedance and a recent study in our laboratory of 26 females and 24 males indicating a significant, yet small, gender difference in ear canal volume (0.37 ml) suggest that the results of this study would have been no more than slightly altered if more males had been included. The effects of age relative to head size, ear canal volume, and skull impedance on
the amount and variability of acoustic radiation in the ear canal during BC stimulation is warranted.

CONCLUSIONS

1. Excessive acoustic radiation from the Radioear B-71 BC vibrator into the EAC appears to be significant only at 4000 Hz.
2. Excessive acoustic radiation from the Radioear B-71 BC vibrator is most likely to occur when the BC vibrator is placed on the mastoid of the test ear.
3. Excessive acoustic radiation from the Radioear B-71 BC vibrator is rarely a concern when the BC vibrator is placed on the forehead and is never a problem when the BC vibrator is placed on the mastoid contralateral to the test ear.

CLINICAL IMPLICATIONS

1. False air-bone gaps due to acoustic radiation from the Radioear B-71 BC vibrator into the EAC are most likely to occur when the frequency of stimulation is 4000 Hz.
2. False air-bone gaps due to acoustic radiation from the Radioear B-71 BC vibrator are most likely when the BC vibrator is placed on the mastoid of the test ear, and are rare when the BC vibrator is placed on the forehead, and are never a problem when the BC vibrator is placed on the mastoid contralateral to the test ear.
3. When a high-frequency air-bone gap occurs with the BC vibrator placed either on the mastoid of the test ear or on the forehead, the clinician can eliminate the possibility that the air-bone gap is due to excessive acoustic radiation from the BC vibrator by placing the BC vibrator on the mastoid contralateral to the test ear, while masking the nontest ear.

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REFERENCES


