False air-bone gaps at 4 kHz in listeners with normal hearing and sensorineural hearing loss

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ABSTRACT

Objective: This report presents data from four studies to examine standard bone-conduction reference equivalent threshold force levels (RETFL), especially at 4 kHz where anomalous air-bone gaps are common. *Design:* Data were mined from studies that obtained air- and bone-conduction thresholds from normal-hearing and sensorineural hearing loss (SNHL) participants, using commercial audiometers and standard audiometric transducers. *Study sample:* There were 249 normal-hearing and 188 SNHL participants. *Results:* (1) Normal-hearing participants had small air-bone gaps at 0.5, 1.0, and 2.0 kHz (-1.7 to 0.3 dB) and larger air-bone gaps at 4 kHz (10.6 dB). (2) SNHL participants had small air-bone gaps at 0.5, 1.0, and 2.0 kHz (-0.7 to 1.7 dB) and a larger air-bone gap at 4 kHz (14.1 dB). (3) The 4-kHz air-bone gap grew with air-conduction threshold from 10.1 dB when the air-conduction threshold was 5–10 dB HL to 21.1 dB when the air-conduction threshold was greater than 60 dB. (4) With the 4-kHz RETFL corrected by the average SNHL air-bone gap, the relationship between RETFL and frequency is linear with a slope of − 12 dB per octave. *Conclusions:* The 4-kHz air-bone gaps for listeners with SNHL could be avoided by adjusting the 4-kHz RETFL by − 14.1 dB.

Key Words:: Audiometry, automated audiometry, hearing, hearing test, air conduction, bone conduction, threshold, air-bone gap, artificial mastoid

Abbreviations

AMTAS	Automated method for testing auditory sensitivity
ANSI	American National Standards Institute
HL	Hearing level
RETFL	Reference equivalent threshold force level
SNHL	Sensorineural hearing loss

Although bone-conduction testing has been part of clinical hearing evaluation since the 1920s (Jones & Knudson, 1924), the first physical calibration standard for normal thresholds appeared in the 1972 American audiometer standard (ANSI S3.13–1972). In subsequent American and international standards, the reference equivalent threshold force levels (RETFLs) were modified slightly and values were added for additional frequencies, but the values in the 1972 standard are very close to those in the current standards (ANSI S3.6 – 2010; ISO 389.3 – 1994).

A complicating factor in the specification of normal bone- conduction sensitivity is related to the calibration devices used to measure the output of the bone vibrator. These devices, called *artificial mastoids*, are based on the premise that the measuring device had to have mechanical impedance properties that are similar to those of the average adult human mastoid. There were two commercially-available artificial mastoids when much of the early normative work was done, the Beltone Model 5A and the Bruel & Kjaer Type 4930 (Wilber, 1972). Another device was developed at the National Physical Laboratory in the UK (Whittle, 1965) and was not commercially available. The Beltone device has been out of production for many years but it was the calibration device used in many of the early studies. The Bruel & Kjaer device is still available and is used widely. A device manufactured by Larson Davis (Model AMC493) mimics the transfer function of the Bruel & Kjaer device and provides another option. Margolis and Stiepan (2012) and Ginter and Margolis (in press) Ginter S.M. & Margolis R.H. In press. Acoustic method for calibration of audiometric bone vibrators. II. Harmonic distortion. JASA Express Letters. challenged the premise that the calibration device must mimic the properties of the head and offered in its place the requirement that the device must provide a stable, reproducible output that could be related to the normal threshold of audibility. They argued that it is not necessary for the device to have the properties of the head, only that the relationship between the values measured on the device and the stimulus levels delivered to the head be consistent.

Soon after the appearance of the first standard RETFLs, clinicians began to notice air-bone gaps at 4 kHz in participants with normal middle-ear function. There was a concern that acoustic radiation from the bone vibrator could contaminate bone-conduction threshold measurements and studies were performed to explore that hypothesis (Whittle, 1965; Lightfoot, 1979; Bell et al, 1980; Frank & Holmes, 1981.; Robinson & Shipton, 1982; Shipton et al, 1980; Frank & Crandell, 1986; Lightfoot & Hughes, 1993). Frank and Holmes (1981) found no difference between 4-kHz bone-conduction thresholds with the test ear plugged and unplugged, indicating that acoustic radiation did not affect the bone-conduction threshold. Bell et al (1980) reported an average difference of 3 dB between occluded and unoccluded bone-conduction thresholds at 4 kHz with a Radioear B71 vibrator, suggesting a small effect of acoustic radiation at that frequency. Frank and Crandell (1986) reported levels of acoustic radiation from two Radioear B71 vibrators that could produce air-bone gaps averaging about 4 dB. Lightfoot's (1979) results suggested that a 4-kHz air-bone gap of about 5 dB could result from acoustic radiation of the Radioear B71 vibrator. Shipton et al (1980) reported that the sound pressure at the entrance of the ear canal for a 4-kHz, 0-dB HL bone-conduction stimulus delivered to the mastoid is about 7 dB SPL, close to the normal threshold of hearing. Because the level measured in the ear canal is typically less than required to affect the measured bone-conduction threshold (Bell et al, 1980), the levels observed by Shipton et al (1980) suggest that acoustic radiation has no significant effect on bone-conduction thresholds. Lightfoot and Hughes (1993) reported no significant difference in 4-kHz bone conduction thresholds with the test ear occluded and unoccluded, suggesting no effect of acoustic radiation at that frequency. Significant effects were observed at higher frequencies. To summarize the results of measurements of acoustic radiation emanating from Radioear B71 bone vibrators at 4 kHz, there may be a small enhancement of the signal level that could lead to a small (0–5 dB) air-bone gap *provided that the acoustic radiation is not incorporated into standard RETFLs* (discussed below*).*

It is important to note that a conductive hearing loss would effectively block the acoustic radiation so the air-bone gap would not be affected by acoustic radiation. Some of the early studies of normal sensitivity to bone-conducted signals attempted to block the acoustic radiation from entering the ear canal (Whittle, 1965; Shipton et al, 1980; Robinson & Shipton, 1982). In other studies (e.g. Wilber & Goodhill, 1967; Dirks & Kamm, 1975; Dirks et al, 1979), the test ear was unoccluded, so any effect of acoustic radiation would be incorporated into the threshold values that were considered in the determination of the RETFLs. The 4-kHz air-bone gaps reported by Margolis et al (2010) with forehead placement of the bone vibrator and a circumaural cushion over the test ear provide strong evidence that the large air-bone gaps that are frequently observed in clinical studies and in clinical practice for participants without conductive hearing loss cannot be attributed to acoustic radiation.

It appears that the problem of inappropriate 4-kHz air-bone gaps has existed for at least four decades.

Dirks et al (1979) reported the results of a multi-site study to obtain normative bone-conduction threshold data for the Radioear B71 bone vibrator calibrated on the Bruel & Kjaer Type 4930 artificial mastoid. Their mean normal threshold for mastoid bone conduction at 4 kHz was 31.2 dB re 1 μN, about 4 dB lower than the 35.0 dB value in the 1972 American standard (ANSI S3.13 – 1972). Perhaps as a result of that study, the RETFL was reduced to 31.0 dB in the 1981 version of the standard. That helped to decrease the false air-bone gaps at 4 kHz. But in the 1996 standard (ANSI S3.6–1996), the value was raised again, this time to 35.5 dB re 1 μN.

To test the validity of their normative bone-conduction threshold values, Dirks et al (1979) tested a group of participants with sensorineural hearing loss (SNHL) with bone-conduction stimuli calibrated to the normative values obtained in the multi-site study of normal-hearing participants. The air-bone gaps for the SNHL participants were essentially zero at all test frequencies including 4 kHz. Their finding at 4 kHz is difficult to reconcile with the observations that will be presented in this article and with widespread informal reports of audiologists who find frequent occurrences of 4-kHz air-bone gaps.

In a study designed to validate an automated pure-tone audiometry method (AMTAS), Margolis et al (2010) reported air-bone gaps from participants with SNHL that averaged 19.3 dB for AMTAS (with bone-conduction thresholds measured with forehead placement of the vibrator and both ears covered by circumaural earphones) and 13.2 dB for manual audiometry (with mastoid placement of the vibrator and the test ear unoccluded). In a follow-up study (Margolis & Moore, 2011) 4-kHz air-bone gaps for participants with SNHL averaged 10.8 dB for AMTAS and 13.4 dB for manual audiometry.

For this report we mined data from published and unpublished studies to obtain the best possible estimate of the 4-kHz air-bone gap for participants with normal hearing and SNHL, in order to provide a basis for estimating a more accurate value of the RETFL at 4 kHz and eliminating the anomalous air-bone gaps that occur in research studies and clinical practice.

Methods

Studies were selected that measured air- and bone-conduction thresholds for participants with normal hearing and with SNHL using manual and automated audiometry (AMTAS). A series of validation studies has demonstrated good agreement between AMTAS and manual audiometry performed by highly-experienced audiologists (Margolis et al, 2007, 2010, 2011; Margolis & Moore, 2011; Eikelboom et al, 2013). Each study used a clinical audiometer calibrated to American (ANSI S3.6 – 2010) or international (ISO 389.3–1994) standards[1] with standard transducers (TDH-type supra-aural earphones or Sennheiser HDA 200 circumaural earphones, and Radioear B71 bone vibrators). For Studies 2 and 3, calibration was performed at the University of Minnesota Audiology Research Laboratory using standard audiometer calibration equipment and a recently calibrated Bruel and Kjaer Type 4930 Artificial Mastoid. For Studies 1 and 4, calibration was performed by the audiometer manufacturer (GN Otometrics).

During bone-conduction testing, masking was applied to the non-test ear and the test ear was unoccluded for manual audiometry but not for AMTAS. Normal hearing was defined as air-conduction thresholds at 0.5, 1.0, 2.0, and 4.0 kHz less than or equal to 20 dB HL. In order to measure the 4-kHz air-bone gap without limitation by a ‘floor effect’, if the 4-kHz air conduction threshold was < 5 dB HL, that participant was eliminated from the analysis. SNHL was defined as four-frequency, air-conduction, pure-tone averages greater than 20 dB with air-bone gaps at 0.5, 1.0, and 2.0 kHz less than or equal to 5 dB. A brief description of each study follows.

Study 1 (Margolis et al, 2010)

Participants with SNHL were recruited and tested at the University of Cambridge. Most participants had participated in previous auditory research studies. Each participant was tested using manual audiometry by an experienced audiologist and using AMTAS. Sennheiser HDA 200 earphones were used for manual testing and for AMTAS.

Study 2 (Margolis & Moore, 2011)

Participants were tested at the Audiology Research Laboratory of the University of Minnesota Hospital. Normal-hearing participants were volunteers recruited from the staff and student population of the university. SNHL participants were recruited from the Audiology Clinic. Each participant was tested using manual audiometry by an experienced audiologist and using AMTAS. Telephonics TDH-50 earphones were used for manual audiometry. Sennheiser HDA 200 earphones were used for AMTAS testing.

Study 3 (Margolis, Johnson, & Ginter, unpublished)

Participants were tested at the Audiology Research Laboratory of the University of Minnesota Hospital. (Procedures were identical to those of Margolis & Moore, 2011 Margolis R.H. & Moore B.C.J. 2011. Automated method for testing auditory sensitivity: III. Sensorineural hearing loss and air-bone gaps. *Int J Audiol*, 50, 440–447.[Taylor & Francis Online], except for the anti-bias method described below). Normal-hearing participants were volunteers recruited from the staff and student population of the university. SNHL participants were recruited from the Audiology Clinic. Each participant was tested using manual audiometry by an experienced audiologist and using AMTAS. Telephonics TDH-50 earphones were used for manual audiometry. Sennheiser HDA 200 earphones were used for AMTAS testing. To avoid bias during manual bone-conduction testing, offsets ranging from − 10 to 10 dB were introduced into the bone-conduction calibration constants stored by the audiometer. These offsets were removed before final analysis.

Study 4 (Eikelboom & Swanepoel, unpublished)

Participants were from the Busselton Healthy Ageing Study (BHAS), a detailed survey of the health of up to 4000 residents in the Shire of Busselton, Western Australia (See Swanapoel et al, in press, for a description of the project). All non-institutionalized participants (born between 1946 and 1964) listed on the electoral roll (n = 6690) and resident in the Shire are eligible to participate. Enrolment into the study is randomized, with 10% of the available sample drawn and recruited at a time. Data used in this analysis were from the first 1004 participants (collected between May 2010 and July 2011); participants were therefore aged 45 to 65 years at the time of examination. Each participant was tested using AMTAS with Sennheiser HDA 200 earphones.

Results

Normal-hearing participants

Mean air-bone gaps, sample sizes, and weighted means for normal-hearing participants from two studies are presented in Table 1. Manual testing was performed with both mastoid and forehead vibrator placement in one study (Study 3). Automated testing with forehead vibrator placement was performed in another study (Study 4). Small air-bone gaps were evident at 0.5, 1.0, and 2.0 kHz (− 1.7 to 0.3 dB). At 4.0 kHz the weighted mean air-bone gap was 10.6 dB.

Table 1. Mean air-bone gaps (air-conduction threshold minus bone-conduction threshold) for normal-hearing participants. The number of ears is indicated by n.

				Frequency (kHz)			
	Method	***BC location***		***0.5***	***1***	***2***	***4***
Study 3	Manual	Mastoid	Mean	0.0	3.4	− 1.3	5.6
			n	16	16	16	16
	Manual	Forehead	Mean	− 1.8	6.1	− 4.6	6.8
			n	14	14	14	14
Study 4	AMTAS	Forehead	Mean	0.4	− 0.3	− 1.5	11.1
			n	235	235	235	235
All		Both	Weighted mean	0.3	0.2	− 1.7	10.6
			n	265	265	265	265
		Mastoid	Weighted mean	0.0	3.4	− 1.3	5.6
			n	16	16	16	16
		Forehead	Weighted mean	0.3	0.0	− 1.7	10.9
			n	249	249	249	249

The weighted mean air-bone gap for forehead placement was 5.3 dB larger than for mastoid placement. However, in the study in which both mastoid and forehead placement was used, the difference was much smaller, 1.2 dB. The larger difference between weighted means for the two bone-vibrator locations was probably related to a difference in study location and participant population rather than to the difference in bone-conductor placement.

Sensorineural hearing loss participants

Mean air-bone gaps, sample sizes, and weighted means for SNHL participants from four studies are presented in Table 2. In three studies (Studies 1, 2, and 3) manual testing was performed with mastoid placement and AMTAS was performed with forehead placement. In Study 4 AMTAS only was performed with forehead placement. Small air-bone gaps were evident at 0.5, 1.0, and 2.0 kHz (− 0.7 to 1.7 dB). At 4.0 kHz the weighted mean air-bone gap was 14.1 dB. The larger air-bone gap at 4 kHz for the SNHL participants than for the normal-hearing participants is an unexpected result and is discussed below.

Table 2. Mean air-bone gaps (air-conduction threshold minus bone-conduction threshold) for participants with sensorineural hearing loss. The number of ears is indicated by n.

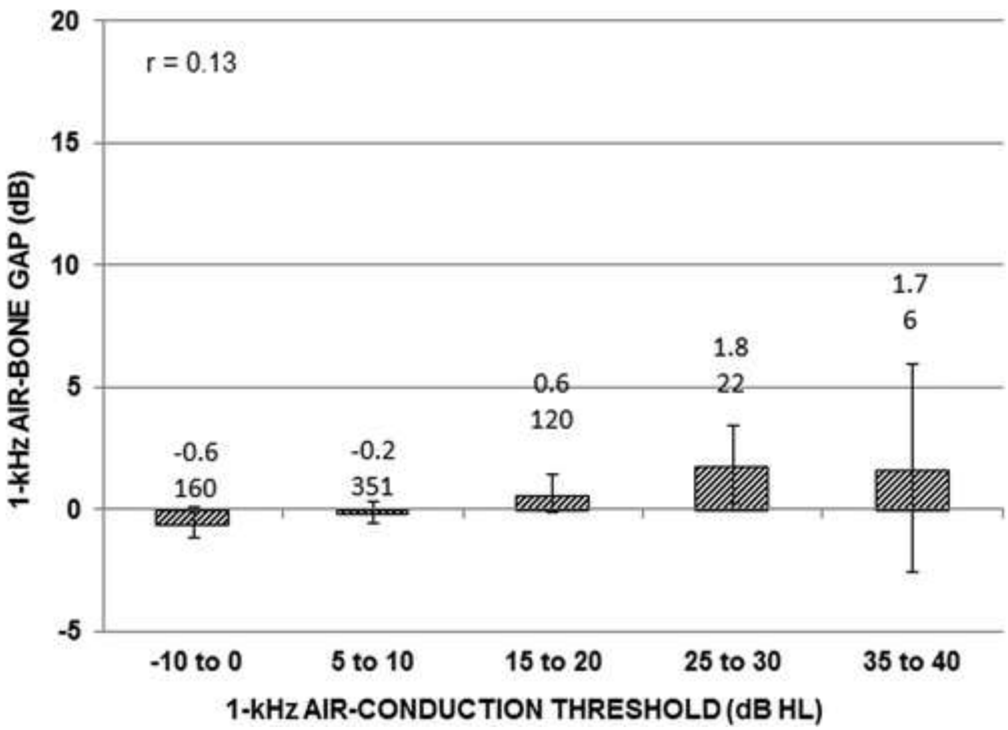
				Frequency (kHz)			
	Method	***BC location***		***0.5***	***1***	***2***	***4***
Study 1	Manual	Mastoid	Mean	1.3	1.0	− 0.5	12.5
			n	20	20	20	20
	AMTAS	Forehead	Mean	4.6	1.7	2.5	20.0
			n	15	15	116	19
Study 2	AMTAS	Forehead	Mean	− 8.4	2.8	− 6.6	10.8
			n	17	18	19	20
	Manual	Mastoid	Mean	− 5.0	− 2.2	− 6.8	13.4
			n	16	19	20	20
Study 3	AMTAS	Forehead	Mean	6.5	5.2	9.3	17.4
			n	23	24	20	16
	Manual	Mastoid	Mean	5.3	3.9	1.4	12.2
			n	27	29	25	16
Study 4	AMTAS	Forehead	Mean	0.8	0.6	− 1.9	13.7
			n	63	63	63	63
All		Both	Weighted mean	1.2	1.7	− 0.7	14.1
			n	181	188	183	172
		Mastoid	Weighted mean	1.4	1.3	− 1.7	12.7
			n	63	68	65	56
		Forehead	Weighted mean	1.1	2.0	− 0.2	14.7
			n	118	120	118	116

The weighted mean air-bone gap was 2.0 dB larger for forehead placement than for mastoid placement. This difference is comparable to the 1.2 dB difference for normal participants in Study 3 but smaller than the 5.3 dB difference for normal participants when Study 4 was included.

Discussion

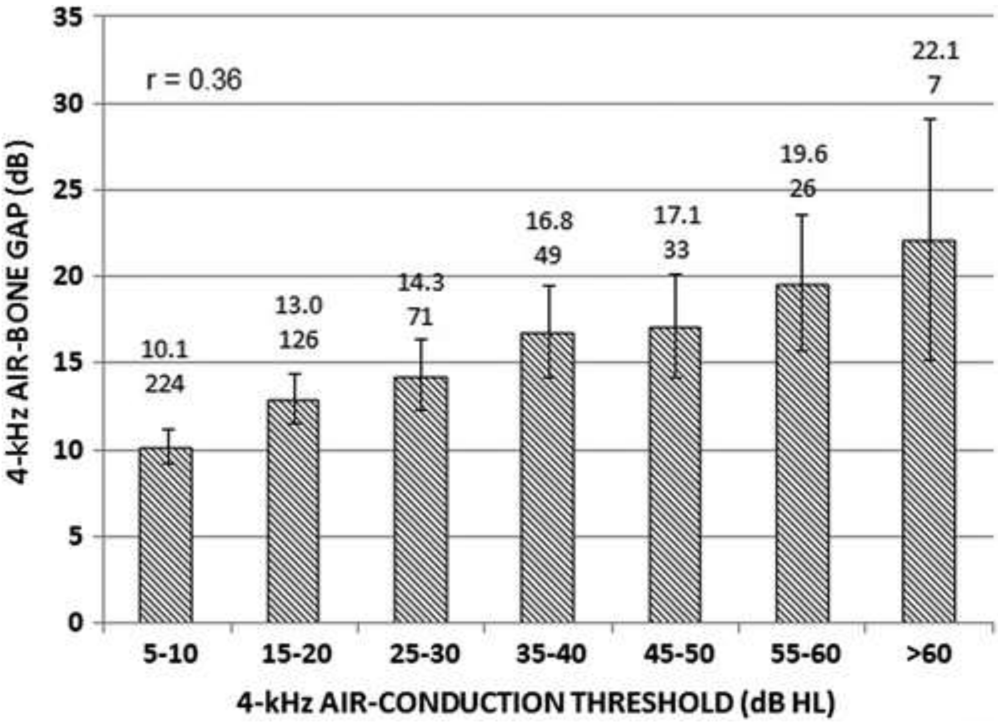
The difference between 4-kHz air-bone gaps for the normal-hearing and SNHL groups suggests that, in the absence of middle-ear dysfunction, bone-conduction threshold and air-conduction threshold are not affected equally by SNHL at that frequency. This finding contradicts a commonly held principle that the air-bone gap should be zero for listeners with normal hearing and various degrees of SNHL. The large sample size tested in Study 4 offers an opportunity to examine the relationship between the air-bone gap and the magnitude of the hearing loss. Figure 1 shows the mean 1-kHz air-bone gap for groups stratified by the 1-kHz air-conduction threshold. The small correlation coefficient between air-bone gap and air- conduction threshold (r = 0.13) and the overlapping 95% confidence intervals suggest that air-bone gaps are unrelated to the magnitude of the SNHL, as expected.

Figure 1. Average 1-kHz air-bone gaps for participant groups stratified by the 1-kHz air-conduction threshold. Data from Eikelboom & Swanepoel, unpublished. Data labels are average air-bone gap and sample size. Vertical lines are 5% confidence intervals.



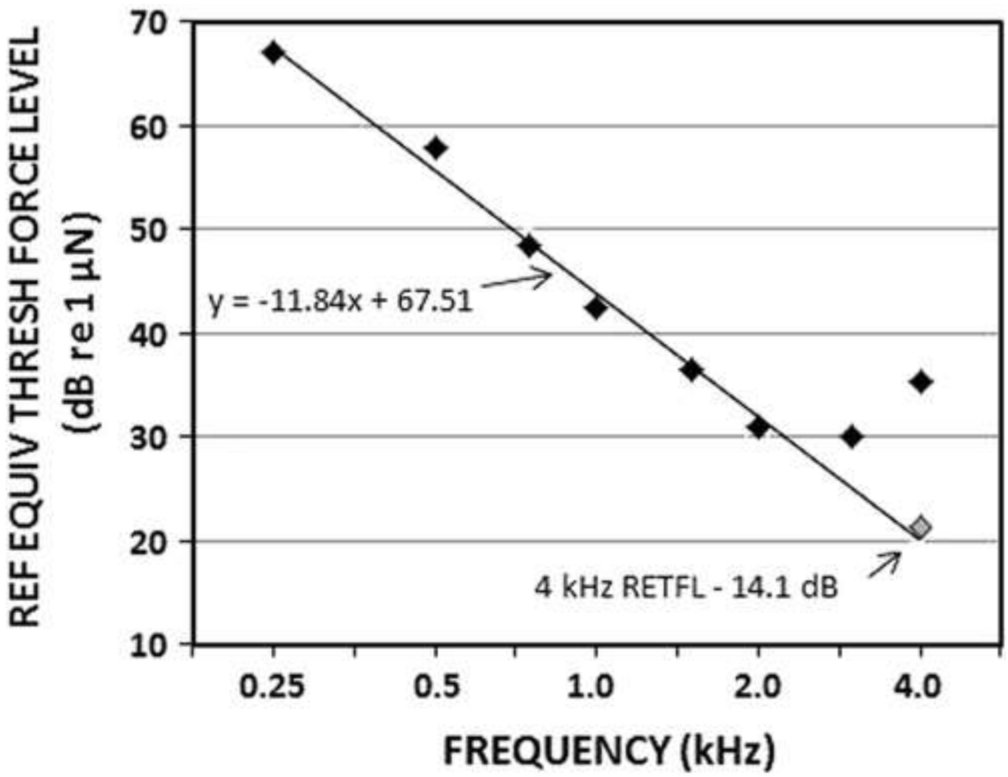
At 4 kHz the picture is quite different (Figure 2). The stronger correlation coefficient (r = 0.36) and the non-overlapping confidence intervals between the mildest and most severe hearing losses indicate a dependence of the air-bone gap on the magnitude of the SNHL at that frequency. The air-bone gap increases monotonically with increasing 4-kHz air-conduction threshold, from 10.1 dB for participants with 4-kHz air-conduction thresholds of 5 or 10 dB HL to 20.1 dB for participants with 4-kHz air-conduction thresholds above 60 dB HL. This surprising result suggests a dependence of the air-bone gap on cochlear sensitivity for participants with normal middle-ear function.

Figure 2. Average 4-kHz air-bone gaps for participant groups stratified by the 4-kHz air-conduction threshold. Data from Eikelboom & Swanepoel, unpublished. Data labels are average air-bone gap and sample size. Vertical lines are 5% confidence intervals.



Early studies of bone-conduction sensitivity indicated *greater* sensitivity (lower threshold) at 4 kHz than at 2 kHz. Lybarger (1966) assembled normal bone-conduction sensitivity data from nine studies and offered interim values for calibration of audiometers. Based on measurements made on the Beltone 5A artificial mastoid, normal thresholds at 4 kHz were 8 dB *lower* than at 2 kHz. Wilber and Goodhill (1967) reported a normal bone-conduction threshold at 4 kHz that was 14.3 dB *lower* than the threshold at 2 kHz. Whittle (1965), using different bone vibrators and a different artificial mastoid, reported bone-conduction thresholds expressed as displacement levels that decreased monotonically with increasing frequency from 0.125 Hz to 5 kHz. When expressed in acceleration units (the second derivative of displacement), the thresholds were constant over that range, indicating a slope in the displacement values of − 12 dB/octave, virtually identical to the slope in Figure 3. These studies used the Beltone 5A artificial mastoid or the artificial mastoid developed at the National Physical Laboratory (Whittle, 1965).

Figure 3. Bone conduction Reference Equivalent Threshold Force Levels from audiometer standards (ANSI S3.6–2010; ISO 389.3–1994). Black-filled diamonds show RETFLs from the standards. The gray-filled diamond is the standard RETFL corrected by − 14.1 dB. The solid line is the best-fit linear regression line fit to the data from 0.25 to 2.0 kHz and extrapolated to 4.0 kHz. The variable × in the regression equation is equal to the number of octaves above 0.25 kHz.



The studies that used the Bruel and Kjaer 4930 artificial mastoid show a different relationship between normal bone-conduction threshold and frequency. Dirks and Kamm (1975), Dirks et al (1979), and Robinson and Shipton (1982) showed normal bone-conduction thresholds that were 0–4.5 dB *higher* at 4 kHz than at 2 kHz. Dirks and Kamm (1975 performed measurements with the same bone vibrator on both the Beltone 5A and the Bruel and Kjaer 4930 artificial mastoids and found large differences for frequencies in the 2–4 kHz region. Threshold levels measured on the Beltone 5A artificial mastoid were 5.7 dB *lower* at 4 kHz than at 2 kHz, while threshold levels measured on the Bruel and Kjaer 4930 artificial mastoid were 3.3 dB *higher*. The current standard RETFL is 4.5 dB *higher* at 4 kHz than at 2 kHz.

Dirks and Kamm (1975) suggested that measurements using the Bruel and Kjaer artificial mastoid may be affected by the mechanical coupling between the bone vibrator and the surface of the device. If there have been changes in the device or its coupling arrangement in the thirty years since those early studies were done, such that the output at 4 kHz has changed, it could result in higher stimulus levels at 4-kHz and false air-bone gaps. This could explain the lack of air-bone gap for the participants with SNHL tested by Dirks et al (1979), which is in stark contrast to the results in Figure 2 of this article.

Figure 3 shows the current standard RETFLs and an adjusted RETFL at 4 kHz. The shaded diamond shows the standard 4-kHz RETFL corrected by the weighted mean 4-kHz air-bone gap for SNHL participants from Table 2 (14.1 dB). The standard RETFLs and the corrected 4-kHz value are described well by a regression line that has a slope of about − 12 dB per octave, very similar to the slope that fits the data of Whittle (1965) and Wilber and Goodhill (1967). However, the standard 4-kHz RETFL falls well above the regression line.

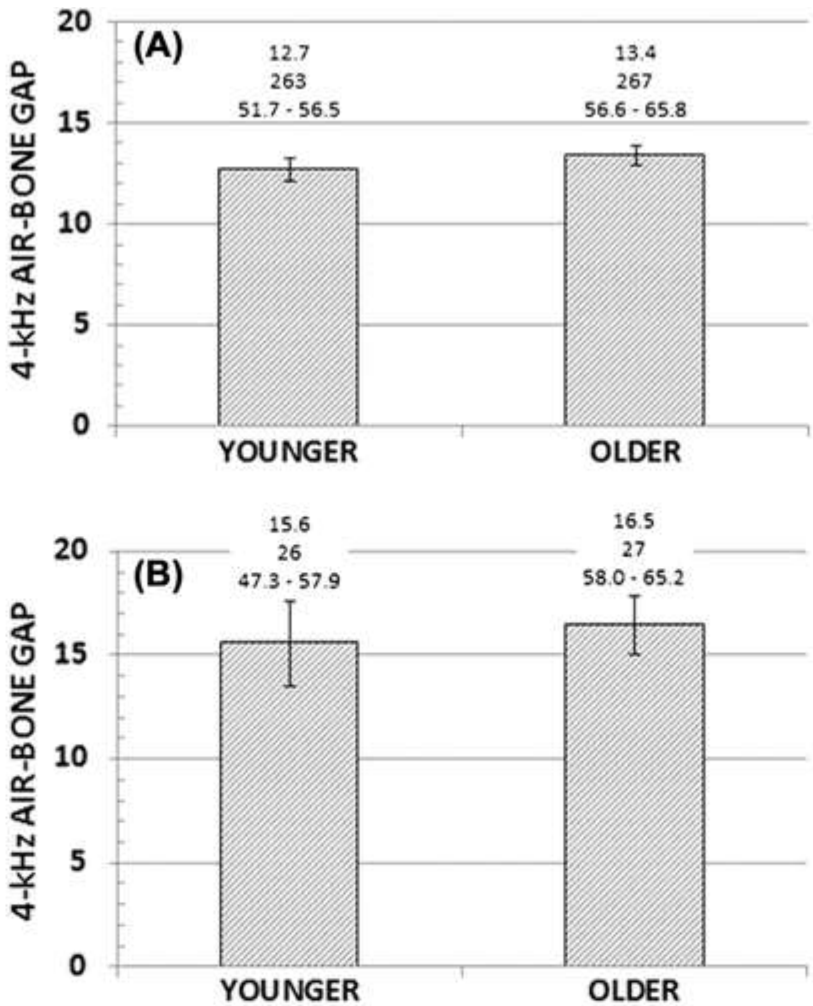
The studies that are included in this analysis did not obtain enough data at 3 kHz to provide a useful analysis. Figure 3 suggests that, because the 3-kHz RETFL falls above the − 12 dB/octave regression line, the RETFL at that frequency may also be too high. Data are needed at this frequency to determine if a change in the RETFL should be made.

The linear behavior (on logarithmic coordinates) of bone- conduction threshold force levels with the 4-kHz correction is striking. It indicates that the force delivered to the soft tissue of the head required to reach the detection threshold decreases at a rate of 12 dB per octave. This orderly relationship results from complex transformations that occur as the bone-conducted stimulus is transmitted from the surface of the head to the cochlear detection system. It is somewhat surprising that the complex transmission pathway would produce a function with a constant slope.

The dependence of the 4-kHz air-bone gap on hearing-loss magnitude that is evident in Figure 2 is troubling because it challenges a widely-held assumption that air- and bone-conduction sensitivity are equally affected by SNHL when middle-ear function is normal. One possibility is that the participants we classified as having SNHL actually had a conductive component at 4 kHz. A source of the conductive component could be an age-related change in middle-ear transmission that affects the 4-kHz air-conduction threshold but not the bone-conduction threshold. Results from Nixon et al (1962) support this hypothesis. They studied patients with age-related hearing loss who were carefully screened for other sources of SNHL, such as noise exposure and otologic disease. Their results indicate a greater effect of age on air-conduction threshold than on bone-conduction threshold at 4 kHz, but not for lower frequencies. Additional evidence of an age-related change in middle-ear function was provided by Feeney and Sanford (2004), who reported a difference in middle-ear acoustic reflectance at 4-kHz between older and younger participants.

We looked for evidence of an age-related component of the 4-kHz air-bone gaps in the results of Study 4. We hypothesized that if there is an age-related difference in middle-ear transmission at 4 kHz, the older group would have a greater air-bone gap than the younger group. A split-half analysis based on age indicated no effect of age on the 4-kHz air-bone gap (Figure 4, A). To explore the possibility that an age effect is evident only for participants with greater hearing losses, we narrowed the group to those with 4-kHz air- conduction thresholds above 35 dB. Again, no age effect was evident (Figure 4, B).

Figure 4. 4-kHz air-bone gaps from younger and older groups of participants. A. Participants with air-bone gaps at 0.5, 1.0, and 2.0 kHz ≤ 5 dB and 4-kHz air conduction thresholds greater than 0 dB HL. B. Participants with air-bone gaps at 0.5, 1.0, and 2.0 kHz < 5 dB and 4-kHz air conduction thresholds greater than 35 dB HL. Data labels are mean air-bone gaps, sample sizes, and age ranges (years). Error bars are ± 1 standard error of the mean.



In an additional analysis, we examined the correlation between age and the air-bone gap at 4 kHz. The correlation was small ($r = 0.09$), and not statistically significant ($p > 0.05$). When the effect of the air-conduction threshold at 4 kHz was partialed out, the correlation became even smaller ($r = 0.025$). The correlation between the air-bone gap and the air-conduction threshold at 4 kHz was significant ($r = 0.355$, $p < 0.01$), and the correlation remained significant ($r = 0.344$, $p < 0.01$) when the effect of age was partialed out. Thus, independent of age, greater hearing loss at 4 kHz seems to be associated with a greater air-bone gap.

These analyses do not support the hypothesis that there is an age-related conductive component at 4 kHz, although it is possible that an effect would have emerged if the groups had spanned a wider age range.

The results confirm previous studies and clinical observations that indicate consistent air-bone gaps at 4 kHz for normal-hearing participants and participants with SNHL when audiometers are calibrated to current standards. These air-bone gaps occur for both mastoid placement and forehead placement of the bone vibrator, using the standard RETFLs for the two locations. Adjusting the 4-kHz RETFL by the average air-bone gap for participants with 4-kHz air-conduction thresholds above 20 dB HL would, on average, eliminate the air-bone gap. Using the same correction for listeners with 4-kHz air conduction thresholds *below* 20 dB HL would result in a small, clinically-insignificant negative air-bone gap.

Summary and Conclusions

Data were mined from four studies that had obtained air- and bone-conduction thresholds from normal-hearing participants and participants with SNHL. The following observations were made based on weighted means from the various studies.

1. Normal-hearing participants have small air-bone gaps at 0.5, 1.0, and 2.0 kHz (− 1.7 to 0.3 dB) and a larger air-bone gap at 4 kHz (10.6 dB). See Table 1.
2. SNHL participants have small air-bone gaps at 0.5, 1.0, and 2.0 kHz (− 0.7 to 1.7 dB) and a larger air-bone gap at 4 kHz (14.1 dB). See Table 2.
3. For groups stratified by the air-conduction threshold, the 1-kHz air-bone gap is small (< 2 dB) and does not vary with hearing loss magnitude (Figure 1). The 4-kHz air-bone gap grows monotonically from 10.1 dB when the pure-tone threshold is 5–10 dB HL to 20.1 dB for participants with pure-tone thresholds greater than 60 dB HL (Figure 2).
4. There is no apparent effect of age on the 4-kHz air-bone gap.
5. If the standard 4-kHz RETFL is corrected by the average air-bone gap for participants with SNHL (14.1 dB), the relationship between RETFL and frequency is a linear function (on logarithmic coordinates) with a slope of − 12 dB per octave.

The results suggest that the 4-kHz air-bone gaps that occur regularly with participants with SNHL are due to an inappropriate RETFL at that frequency. An adjustment of − 14.1 dB would reduce these air-bone gaps to an average of 0 dB for participants with 4-kHz air-conduction thresholds above 20 dB HL. In view of the strong predictive accuracy of the − 12 dB per octave slope, a set of RETFLs that conform to that slope may be appropriate and helpful for defining RETFLs at other frequencies where there are less definitive data (such as 3 and 6 kHz). Because of the relationship shown in Figure 1, a correction of this magnitude may slightly elevate bone-conduction thresholds for participants with normal hearing. This is not a significant concern because: (1) it is common to omit testing bone-conduction when the air-conduction threshold is normal; and (2) a slight elevation in bone-conduction threshold for a normal-hearing participant will not result in a diagnostic error.

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Declaration of interest: The first author is president of Audiology Incorporated (AI) which owns intellectual property that was used in some of the studies reported in this article. That intellectual property may be incorporated into commercial products. AI has developed and plans to commercialize a bone-conduction calibration coupler (described in Margolis and Stiepan, 2012). The other authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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