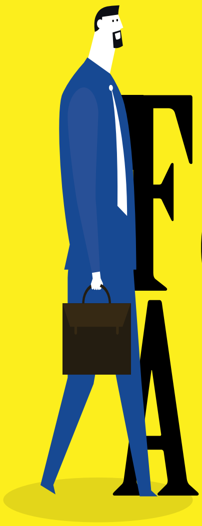


# False 4-kHz Air-Bone Gaps

## A Failure of Standards

BY ROBERT H. MARGOLIS, ROBERT H. EIKELBOOM, BRIAN C.J. MOORE, AND DE WET SWANEPOEL

*This article is a revision of the version published in the November/December 2018 issue. The main purpose of publishing the new version is to clarify* FIGURE 3. *In addition to clarifying the data presented in the original article, we include here a new set of data that recently became available that support the main message (Wassermann, 2018).*

One paper, by Edith Corliss and her colleagues at the U.S. National Bureau of Standards, ignored by standards committees for decades, demonstrates a simple, elegant relationship between normal bone-conduction thresholds and frequency.

During the Eisenhower administration, more than half a century ago, the Third International Congress on Acoustics convened in Stuttgart, Germany. It was a wide-ranging conference covering all areas of psychological, physiological, and physical acoustics. The list of authors from the proceedings is a three-column, three-page Who's Who that includes many of the most eminent auditory scientists of the day. Some of the familiar names on the roster include Georg von Békésy, Nelson Kiang, S.S. Stevens, Juergen Tonndorf, and Eberhard Zwicker.

One paper, presented there by Edith Corliss and her colleagues at the U.S. National Bureau of Standards and ignored by standards committees for decades, demonstrates a simple, elegant relationship between normal bone-conduction thresholds and frequency. The results were described in this way:

"The threshold displacement amplitude decreases with frequency at a slope of 12 dB per octave, thus the magnitude of the acceleration imparted to the head at the threshold of sensation is very nearly independent of frequency" (Corliss, Smith, and Magruder, 1959, p. 54).

Because the Corliss paper has been ignored for the past 59 years by standards committees, we frequently see audiograms like the one in FIGURE 1, obtained in the course of the Busselton Healthy Aging Study, a survey of residents in the Shire of Busselton, Western Australia (Swanepoel et al, 2013). Here, air-bone gaps of 20 dB were obtained in both ears at 4 kHz without air-bone gaps at other frequencies. Recent studies have documented the occurrence of air-bone gaps at 4 kHz in listeners with sensorineural hearing loss and normal middle-ear function. Many audiologists encounter this frequently in their practice.

In this article, the source of this problem and possible solutions are presented.

## THREE STUDIES, THREE DEVICES

The displacement amplitude referred to by Corliss is directly proportional to the force level that is measured during calibration of bone vibrators for audiometry. The threshold force levels decrease with frequency over the audiometric range (0.25–4.0 kHz).

The -12 dB/octave slope is a familiar one in mechanics.[1] It represents a constant acceleration of the system being observed, in this case the vibration of the bone vibrator when the signal is at threshold. Above 4 kHz, thresholds for normal-hearing listeners become so low that they are difficult to measure in the noise floor created by internal and external sources.

The findings of Corliss et al were replicated by Whittle (1965) in the United Kingdom and, with small differences, by Lybarger (1966) in the United States. The three studies used three different devices to measure the vibratory energy produced by bone vibrators. None employed the mechanical coupler used almost exclusively today to calibrate bone-conduction stimuli, the Bruel and Kjaer Type 4930 Artificial Mastoid.

The U.S. and international calibration standards, in lockstep by agreement between their respective standards organizations, don't reflect the robust -12 dB/octave relationship. If they did, the Reference Equivalent Threshold Force Level (RETFL) at 4 kHz would be 12 dB lower than the RETFL at 2 kHz. Instead, the 4-kHz RETFL is 4.5 dB higher than the 2-kHz RETFL. The difference between the RETFL and the value predicted by Corliss et al, 16.5 dB, is almost exactly the magnitude of the false air-bone gaps reported in several studies and observed by audiologists every day.

## A CLOSER LOOK AT STANDARDS

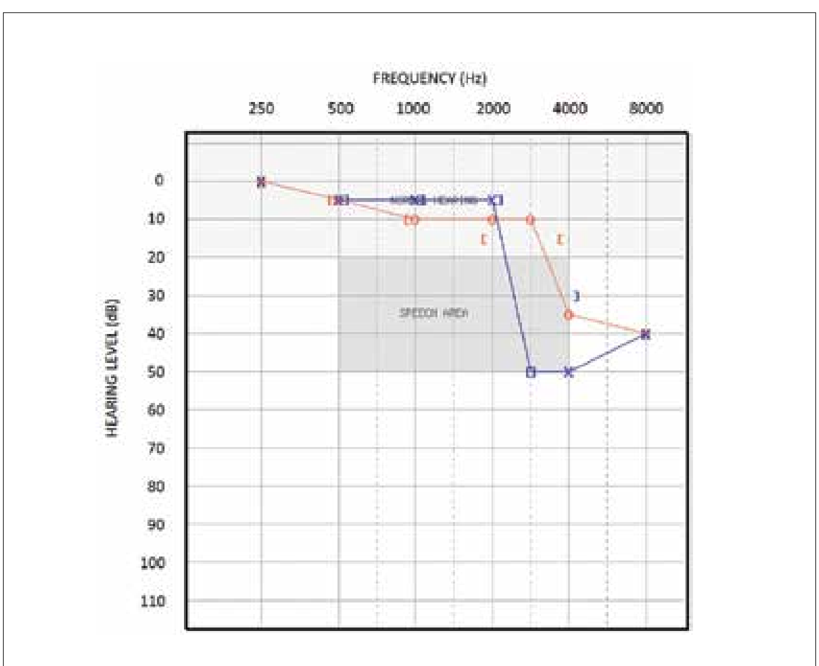
Let's review the function of standards. The American National Standards Institute (ANSI) is a private, non-profit organization that produces standards for many industries. The standards have no legal authority unless there are standards provisions written into law.

Some audiology state licensure laws, for example, require that hearing testing by audiologists must be performed with audiometers calibrated to the current audiometer standard (ANSI S3.6-2018). Other standards may not be written into law, such as the American National Standard Safety Code and Requirements for Dry Martinis, originally published in 1966 (ASA K100.1-1966) and updated in 1974 (ANSI K100.1-1974).

Although they are not required to do so, instrument manufacturers usually comply with relevant standards because they want to be able to represent their products as compliant with standards. In addition, standards are usually followed closely by calibration services, although that is not always the case.

Most countries comply with standards that are published by the International Organization for Standardization (ISO), a body of representatives from the national standards organizations of 162 countries, including the United States. Audiometer specifications are provided in several ISO standards, collectively designated ISO 389.

**FIGURE 1.** Audiogram from the Busselton Healthy Ageing Study, with apparent air-bone gaps at 4 kHz.




## RETFLs AND RETSPLs: TIME FOR AN UPDATE

ANSI S3.6-2018 and ISO 389-3:2013 provide the calibration levels for bone conduction, the Reference Equivalent Threshold Force Levels (RETFLs) mentioned earlier. The ANSI standard and other ISO 389 standards provide the air-conduction calibration levels for various earphones, called the Reference Equivalent Threshold Sound Pressure Levels (RETSPLs).

It is desirable for the RETFLs and RETSPLs to be the same in the American and international standards. Interestingly, counter to the interests of American audiologists and their patients, ANSI committees will not do anything to update RETSPLs and RETFLs, even when evidence indicates that changes are appropriate. The ISO committees also are not taking action in this area on this problem.

The international standard (ISO 389-3) states that the RETFLs are derived from three studies from Germany, the United Kingdom, and the United States. All three used the Bruel and Kjaer artificial mastoid for calibration, in spite of the fact that one study (Dirks et al, 1979) showed performance data on the device that significantly departs from the requirements of the standard that specifies the characteristics of mechanical couplers used for bone-conduction calibration (ANSI S3.13-1987 and its predecessors).

The work of Corliss et al and its replications have been ignored. As a result, the 4-kHz RETFL is 4.5 dB higher than the 2-kHz RETFL, rather than 12 dB lower as the Corliss relationship would dictate.

FIGURE 2 illustrates the disconnect between standard RETFLs and the Corliss relationship between bone-conduction thresholds and frequency. The solid line shows bone-conduction thresholds from the report of Corliss et al (1959). The dashed line shows the RETFLs from the standards. The dotted line shows the -12 dB/octave relationship. The difference between the 4-kHz RETFL and the expected threshold based on the -12 dB/octave slope is 14.1 dB. The 4-kHz RETFL does not correspond to the expected bone-conduction threshold for normal-hearing subjects. It is 14.1 dB higher.

How did this happen? Because the RETFLs are based only on studies that used the Bruel and Kjaer artificial mastoid to measure thresholds, it is likely that the error is related to the calibration device.

In the Dirks et al (1979) paper, structural problems with the calibration device were discussed and mechanical impedance measurements were reported that were substantially different at frequencies above 2 kHz than the impedance requirements in the standard that governs bone-conduction calibration devices (ANSI S3.13).

That doesn't explain the discrepancy, however, because any errors in measured force levels would be incorporated into the determination of the RETFL. If the performance of the device changed after the RETFLs were determined, and those changes were not used to adjust the RETFLs, then the standard RETFLs would incorrectly estimate normal thresholds.

It is likely that changes were made in the device after the three studies that determined RETFLs were conducted, and that the current RETFL corresponds to a threshold that is higher than the actual normal threshold by about 14 dB, roughly the magnitude of the false 4-kHz air-bone gap reported in the studies mentioned previously.

“Because the RETFLs are based only on studies that used the Bruel and Kjaer artificial mastoid to measure thresholds, it is likely that the error is related to the calibration device.”

## A PETITION FOR CHANGE

We became aware of the problem in the first clinical trial of AMTAS (Automated Method for Testing Auditory Sensitivity) conducted at Cambridge University (Margolis et al, 2010). For subjects with sensorineural hearing loss, air-bone gaps at 4 kHz were 19.3 and 13.2 dB for AMTAS and manual audiometry, respectively. Small air-bone gaps (< 5 dB) were observed at other frequencies.

The finding was replicated in a subsequent study with additional data from the United States (Margolis and Moore, 2011), in another with additional data from Australia (Margolis et al, 2013), and in another with a group of

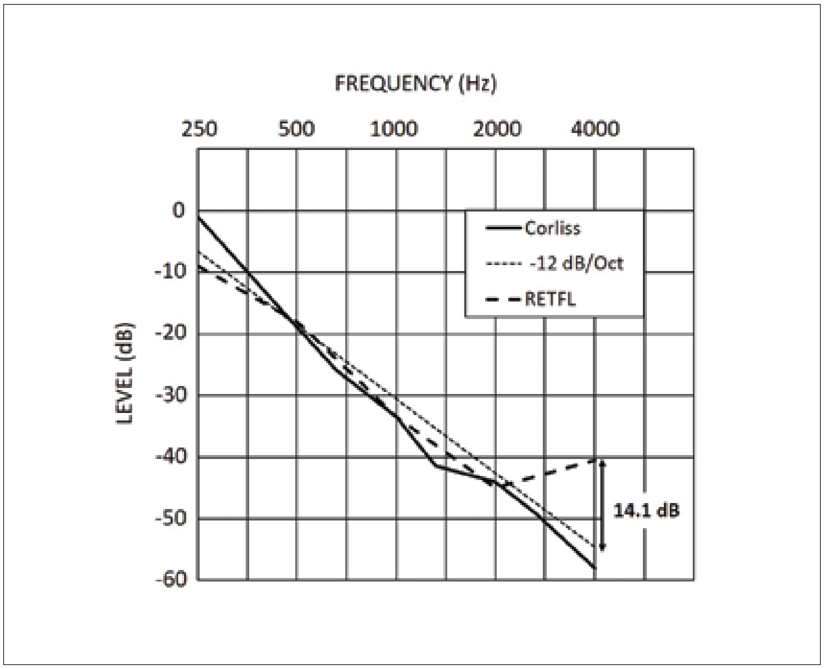



**FIGURE 2.** The solid line illustrates bone-conduction threshold as a function of frequency (Corliss et al, 1959). The dotted line has a slope of -12 dB/octave. The dashed line shows the RETFLs from the audiometer standards.

young normal-hearing subjects (Altus et al, 2018; Rao et al, 2018).

Based on the existing evidence at the time, a petition was presented to the ISO in 2013, requesting a change in the 4-kHz RETFL to eliminate false air-bone gaps at that frequency. The petition was denied, citing insufficient data.

## THE ISO 389-9 STANDARD

The ISO 389-9 standard specifies the requirements for studies from which results can be considered as evidence for modifying RETFLs and RETSPLs. It is the policy of the standards committees that evidence obtained by other methods cannot be considered, no matter how scientifically compelling it may be. The results of Corliss et al (1959), Whittle (1965), Lybarger (1966), and Margolis et al (2010, 2011, 2013) are not considered because they do not meet the requirements of ISO 389-9.

That standard mandates that only data from normal-hearing subjects can be considered, a paradoxically illogical requirement considering that the purpose of pure-tone audiometry is to accurately test people with hearing loss. That policy prohibits consideration of the results shown in FIGURE 3 from Margolis et al (2013), Alton et al (2018), and Wassermann (2018).

The data in FIGURE 3 reveal a surprising finding. The air-bone gap resulting from the incorrect 4-kHz RETFL increases with increasing magnitude of the hearing loss (the air-conduction threshold at 4 kHz). For normal-hearing subjects, the false air-bone gap is 5–10 dB and it increases to 15–20 dB for listeners with a 50-dB sensorineural hearing loss, depending on the threshold measurement method. Margolis et al (2013) and Altus et al (2018) used AMTAS to obtain thresholds. The results from Wassermann (2018) were obtained in an ENT clinic using manual clinical audiometry. The differences in air-bone gaps obtained by the two methods are almost identical to the differences reported by Margolis et al (2010) and may result from unintentional bias during manual testing (Margolis et al 2016). The smaller air-bone gaps for listeners with normal hearing and mild hearing losses probably result from effects of internal and external noise for low-level signals.

The ANSI committee that should pay attention to this is Working Group 35 (of which the first author of this article is a member). But, because ANSI has ceded authority for RETSPLs and RETFLs to the ISO, the committee is not inclined to address the issue.

Some members of WG35 are also on the ISO committee that has authority over RETFLs and RETSPLs and perhaps they will influence the ISO to reconsider its previous denial. But, as long as the policy is to exclude scientific evidence that does not meet certain arbitrary and ill-conceived requirements, it does not seem likely that the issue will be addressed soon.

## NEW STUDIES, NEW FUNDING NEEDED

The standards committees point out to the audiology community that we are free to conduct a study that complies with ISO 389-9 (without offering to fund such a study, of course). Unfortunately, it is not likely that traditional funding sources such as the National Institutes of Health or the National Science Foundation would provide this funding.

A proposal for a study involving Australia, South Africa, Sweden, and the United States was submitted in 2015 to a foundation that supports hearing research for an international partnership. The application was not funded.

A much smaller study (Altus et al, 2018; Rao et al, 2018) conducted at Arizona State University that complies with ISO 389-9 except for some of its ill-conceived requirements (required masking level, fitting of earphones) produced the corroborating evidence shown in FIGURE 3.

## IN THE MEANTIME: THE COPING MECHANISMS

The current situation is that clinicians, without any guidance from standards committees, cope with the problem in different ways. Some report the false air-bone gaps that are subject to misinterpretation as conductive components. Some add a correction factor that varies from one clinic to the next. Some ask their calibration services to calibrate using a corrected 4-kHz RETFL, as suggested by Margolis et al (2013). Others choose not to test bone conduction at 4 kHz.

There are reports that some calibration services calibrate 4-kHz bone-conduction levels off standard to eliminate the false air-bone gaps with or without informing a clinic that they have done so.

The failure of the standards groups to address this problem creates several potential issues for clinicians:

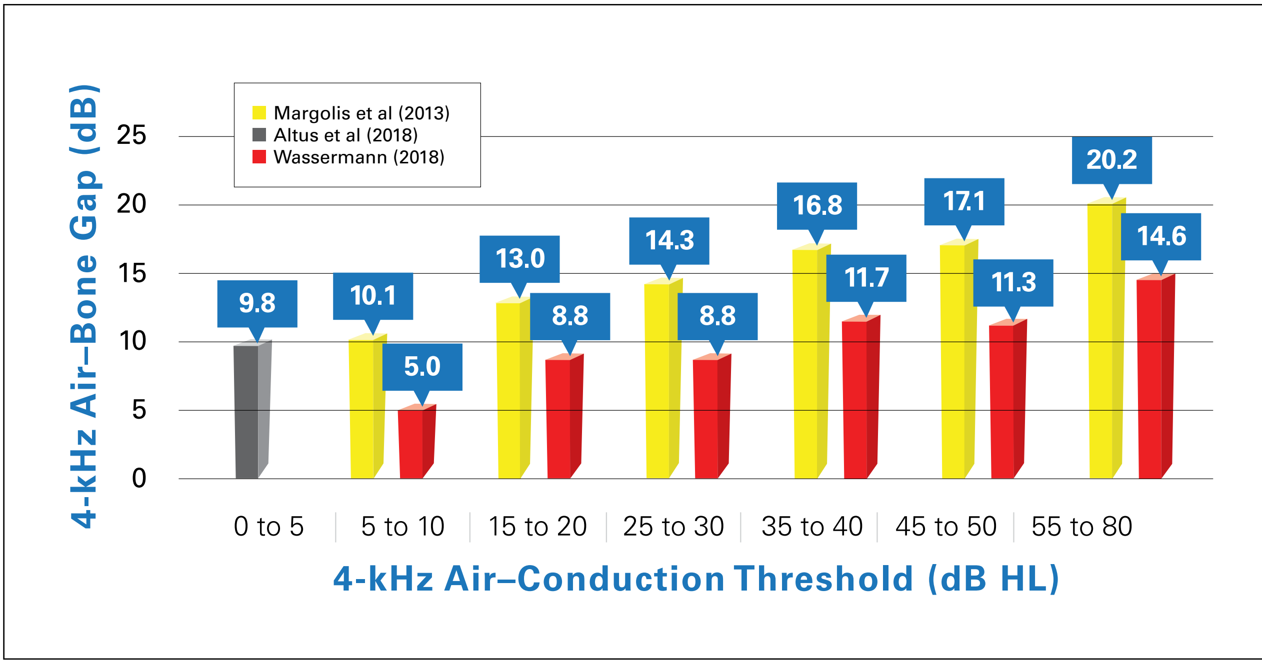



**FIGURE 3.** Average 4-kHz air-bone gaps for subjects with varying degrees of hearing loss from three studies. Data from Margolis et al (2013) and Altus et al (2018) were obtained with automated audiometry (AMTAS). Data from Wassermann (2018) were obtained using conventional manual audiometry in an ENT clinic.

- Reporting false air-bone gaps can result in misinterpretation of test results that could affect medical follow-up, leading to unnecessary tests, unnecessary surgeries, inappropriate treatments, and unnecessary clinic visits.
- Correcting bone-conduction thresholds by a factor that is not endorsed by standards or clinical guidelines places the clinician in a quandary regarding best practice.
- Calibrating 4-kHz bone-conduction levels off standard may violate regulations that require audiometers to be calibrated to standards.
- Reporting false air-bone gaps may affect the credibility of audiometric results. Air-bone gaps such as those in FIGURE 1, in the absence of middle-ear disease, abnormal tympanometry, and otoscopic signs of ear disease can compromise the relationship between audiologists and physicians.

## A POSSIBLE APPROACH

One approach to dealing with the problem may be to develop a written policy, approved by clinic management, citing published literature and specifying the exact plan. For example, the policy could say that 4-kHz bone conduction will be calibrated to a corrected RETFL of 21.4 dB re 1 µN for mastoid bone and 29.4 dB re 1 µN for forehead bone.

Audiologists are responsible to their patients to provide accurate testing that does not result in harmful outcomes. Standards committees are not being held responsible for harm that results from errors in standards. Because it is not likely that any solution will be provided by the standards committees in the foreseeable future, it is up to us to manage this failure of standards.

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## Endnote

[1]The magnitude of sinusoidal signals like the pure tones we use for audiometry can be expressed in units of pressure, displacement, velocity, and acceleration.

When we calibrate audiometers, we express levels in units of pressure in decibels (dB). Pressure and the displacement of the body that is set into vibration (such as the skull) are directly proportional. Velocity is the rate of change of displacement. Acceleration is the rate of change of velocity.

In mathematical terms, the velocity is the first derivative of displacement; acceleration is the first derivative of velocity and the second derivative of displacement. Since velocity is the rate of change of displacement, when we double the frequency we double the velocity.

For a constant velocity, we would have to halve the displacement (and the pressure) every time we double the frequency. A frequency doubling corresponds to one octave.

In logarithmic units, a reduction in pressure or displacement by one half corresponds to 6 dB. So, if pressure or displacement decreases by 6 dB/octave, the velocity remains constant.
A doubling of frequency produces a fourfold increase in acceleration. So, if pressure or displacement decreases by 12 dB/octave, the acceleration remains constant.

The Corliss et al (1959) observation that the bone-conduction threshold decreases with a slope of -12 dB/octave supports their interpretation that the threshold for bone-conducted signals occurs at a constant acceleration over the frequency range of their measurements.

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