Acoustic method for calibration of audiometric bone vibrators

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The standard method for the calibration of audiometric bone vibrators requires the use of an artificial mastoid, a device that converts vibratory energy to an electrical analog. The mechanical input impedance of the device is designed to represent the average mechanical impedance of the human head. For calibration purposes, it is not necessary that the coupling device represent the impedance of the head. It is only necessary that it provides a repeatable measurement of the output of the vibrator that can be related to the normal threshold of hearing at each test frequency. In addition to the mechanical output that serves as the stimulus for the hearing test, bone vibrators produce an acoustic signal that is proportional to the mechanical force delivered to the head. By determining the transfer function relating the acoustic sound pressure to the mechanical force, the acoustic signal can serve as a proxy for the vibratory stimulus. This article describes the design and validation of an acoustic coupler for the calibration of audiometric bone vibrators. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3675007]

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I. INTRODUCTION

Bone-conduction audiometry is an important component of the audiologic evaluation, providing diagnostic information about the site of lesion of an auditory impairment. Because the stimuli are vibratory signals delivered to the head, they must be calibrated differently from the acoustic signals used for air-conduction audiometry. A coupling device is needed to couple the vibrator to a measuring instrument.

The standard coupling device is the artificial mastoid, a device that converts the vibratory signal to an electrical analog signal that can be delivered to a measuring device like a volt meter, oscilloscope, or sound level meter. The principle of the artificial mastoid is that it represents the average mechanical impedance properties of the human head, so that the output is analogous to the signal delivered by the bone vibrator when it is coupled to the head. Sanders and Olsen (1964) averred "basic to the design of an artificial mastoid is the fact that the bone vibrator must be placed on a material or device that will simulate, accurately and reliably, the mechanical impedance of the skin, flesh, and bone of the human mastoid" (p. 248).

American and International standards (ANSI S13.1-1987, IEC 60318-6-2007) specify the mechanical impedance that should be designed into the artificial mastoid. The audiometer standards (ANSI 3.6-2010, ISO 389-3-1994) specify the reference equivalent threshold force levels (RETFLs), the force levels that correspond to normal threshold of hearing for audiometric frequencies. There is one commercially-available artificial mastoid that meets the specifications of the standards (Bruel & Kjaer Type 4930). Another meets the impedance requirements of the standards but not all of the specified physical dimensions (Larson Davis AMD 493). Stenfelt and Håkånsson (1998) designed an artificial mastoid with standard mechanical impedances that provides results that are equivalent to the B&K 4930 at frequencies above 450 Hz.

The approach described in this report is based on a different premise. For the purpose of calibrating audiometric bone vibrators, it is not necessary that the coupling device mimic the mechanical impedance characteristics of the human mastoid. It is only necessary that it provides a reproducible measurement of the output of the device that can be related to the normal threshold of bone-conduction hearing at each test frequency of interest. With this approach, the placement location (mastoid, forehead, or other site) requires only a transfer function that relates the output measurements to behavioral thresholds obtained with the bone vibrator at the desired location.

The approach described here and the AMD 493 artificial mastoid share a reliance on an acoustic signal to infer the force delivered to the head. The LD device does so with a mechanical-to-acoustic transducer that is intended to simulate the mechanical impedance of the head. We have simplified the approach by eliminating any simulation of the properties of the head, which we show below is not necessary to achieve a valid calibration.

There is precedent for this approach in air-conduction calibration. Although the 6-cc couplers used for calibrating audiometric earphones were designed to approximate the acoustic impedance of the ear, subsequent measurements indicated that they do not accurately accomplish that goal. However, the couplers successfully provide repeatable measurements that can be associated with normal air-conduction thresholds. They serve their purpose quite well by providing a standard, repeatable measurement of earphone acoustic output levels.

Bone-conduction vibrators produce vibratory signals that are specified as force levels (in dB re 1.0 μN or dB re 1.0 dyne) for purposes of calibration with artificial mastoids.

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But there is also an acoustic signal that is produced when the vibrating surface of the device is in contact with air. This is easily appreciated by holding the vibrator near the ear, which provides a clearly audible tonal signal. This acoustic radiation has been a concern for many years because of its potential to contaminate threshold measurements for bone-conducted signals. Several studies have reported the conditions under which acoustic radiation does or does not affect bone conduction thresholds (Frank and Holmes, 1981; Fagelson and Martin, 1994; Stenfelt and Reinfeldt, 2007).

The acoustic radiation can be exploited as an output response of the device which is closely correlated with the force level that is delivered to the head during bone-conduction testing. Accordingly, it is possible to determine a reference equivalent threshold sound pressure levels ($RETSPL_{bc}$) at each test frequency that corresponds to the normal threshold of audibility for the vibrator stimulus when the device is coupled to the head. To be reliable, a reproducible coupling arrangement is required to deliver the acoustic signal to a measuring device.

This report describes the development and validation of an acoustic coupler (AMBONE™) that can be used to calibrate audiometric bone vibrators.

II. DESIGN PRINCIPLE

AMBONE™ is designed specifically for the bone vibrator that is most commonly used in audiometry (Radioear B-71, 10-ohm and 50-ohm versions). The bone vibrator is roughly a rectangular solid with one facet having an elevated circular surface which is placed in contact with the head during testing. The entire plastic case vibrates but only the circular facet is placed in contact with the head.

AMBONE is a high-density polyurethane device that couples the bone vibrator to a standard acoustic earphone coupler (IEC 60318-2-1998). A minor redesign would provide compatibility with the NBS-9A coupler described in ANSI S3.7 (1995). It is designed to fit securely and reproducibly on the circular opening of the coupler (Fig. 1). The elevated circular surface of the vibrator is placed in the opening of AMBONE and secured by a weight that delivers the standard coupling force (5.4 N) to the vibrator. The weight has a compliant surface that is in contact with the vibrator to comply with the requirement that the device used to deliver the static force should be decoupled from the vibrator (IEC60318-6-2007, Sec. 7, Note 1). Because the characteristics of the weight and its compliant surface influence the transfer function of the device, this arrangement must be standardized. When coupled to AMBONE, only the elevated circular facet of the bone vibrator is open to the air chamber of the coupler. The important feature is that the coupling is consistent so that the acoustic output is proportional to the vibratory signal delivered to an artificial mastoid or to a human head. To that end, the design ensures that there are no acoustic leaks between the bone vibrator and AMBONE and between AMBONE and the earphone coupler.

III. METHODS

Sound pressure levels were measured with the arrangement illustrated in Fig. 1 for several audiometers and bone vibrators. Measurements made with AMBONE were compared to results obtained with a recently-calibrated artificial mastoid (Bruel & Kjaer 4930). The measuring instrument was a commercial sound level meter (Larson Davis System 824) with a 0.5 in. condenser microphone (Larson Davis model 2559). The sound level meter was calibrated with a commercial device designed for calibration of sound-level meters (Bruel & Kjaer 4230). The calibrator was cross-checked with a second sound level meter which was calibrated with its own calibrator. All measurements were made in a double-wall sound booth. Sound pressure levels for sinusoidal signals were measured in 1/3 octave filters.

IV. RESULTS AND DISCUSSION

The variability of measurements made with AMBONE was assessed for measurements made (a) with five AMBONE devices, (b) on five separate days, (c) for five audiometers each with their own bone vibrator, and (d) for five audiometers with the same bone vibrator. In addition, the linearity of measured levels for varying input levels was observed and reference equivalent threshold sound pressure levels for bone conduction stimuli ($RETSPL_{bc}$) were derived for the AMBONE coupler.

Figure 2 shows variability associated with five AMBONE couplers measure on five days with two audiometers. Averaged across frequency, standard deviations ranged from 0.21 to 0.32 dB with no systematic differences between audiometers. The results indicate that measurements are quite consistent among AMBONE devices.

Figure 3 shows variability associated with the five measurement days for AMBONE couplers and the B&K 4930 Artificial Mastoid for two audiometers. Standard deviations for AMBONE couplers, averaged across the nine measurement frequencies, ranged from 0.27 to 0.44 dB. Average standard deviations for measurements made with the B&K artificial mastoid were 0.80 and 1.00 dB for the Grason Stadler GSI-61 audiometer and the Madsen Aurical audiometer, respectively.

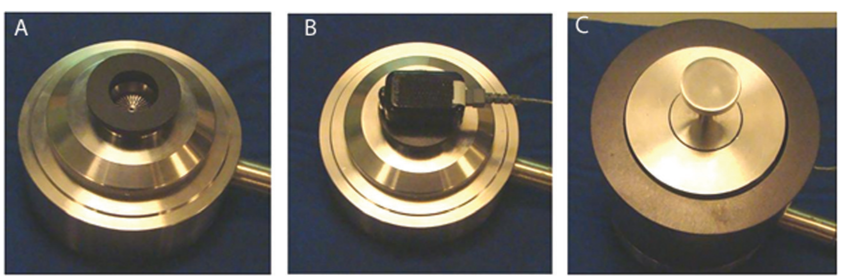

FIG. 1. (A) AMBONE positioned on an IEC 318 earphone coupler. (B) Radioear B-71 bone vibrator placed on AMBONE. (C) Positioner and coupling weight positioned on the coupler. The coupler, positioner, and coupling weight are the Larson–Davis model AEC101 earphone coupler.

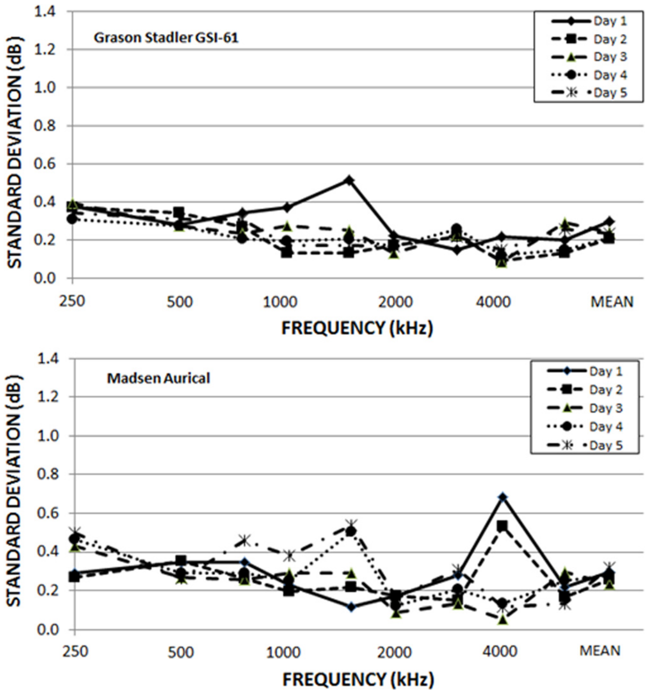

FIG. 2. (Color online) Average standard deviations of sound pressure level measurements made with five AMBONE couplers on five days. Bone conduction signals were produced by two audiometers with Radioear B-71 bone conduction vibrators.

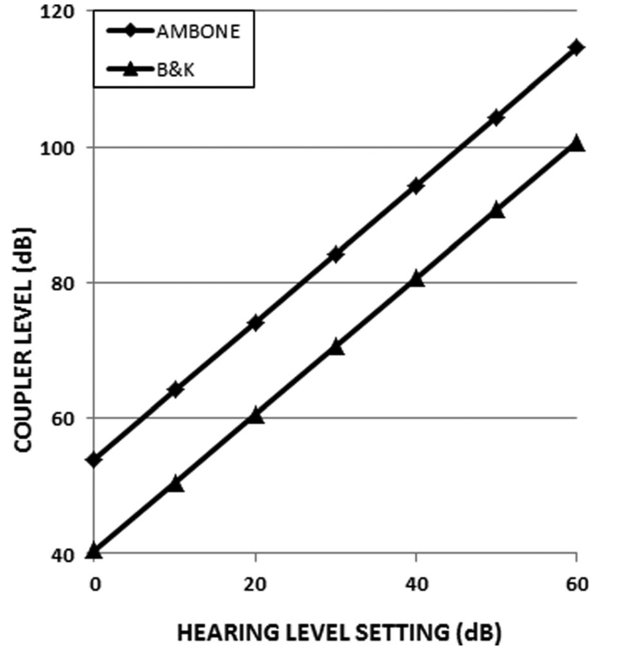

FIG. 4. Linearity of output measures obtained with two coupling devices. Bone-conduction signals (1 kHz) were delivered by an audiometer (Madsen Aurical) to a bone vibrator (Radioear B-71) coupled to a sound level meter (Larson Davis 824) with AMBONE and a B&K Artificial Mastoid. AMBONE levels are sound pressure levels in dB re 20 μPa. B&K levels are force levels in dB re 1 μN.

Figure 4 shows linearity measurements for output levels measured with AMBONE and the B&K artificial mastoid. Signals were delivered by a clinical audiometer (Madsen Aurical) to a bone vibrator (Radioear B-71) coupled to the sound level meter with the two coupling devices for output levels ranging from 0–60 dB HL. The results indicate a high degree of linearity with both coupling devices.

Figure 5 shows results for five audiometers (four Madsen Coneras and one Madsen Aurical) each with their own Radioear B-71 bonevibrator. The Conera audiometers were located in the University of Minnesota Hospital Audiology Clinic. The Madsen Aurical is used in the Audiology Research Laboratory in the University of Minnesota Hospital. Although all audiometers had been calibrated recently, there are likely to be small calibration differences that will affect the measurements made with AMBONE. To control for the calibration variability, measurements are expressed relative to values obtained with the B&K 4930 Artificial Mastoid. Ideally there would be a fixed relationship between measurements made with AMBONE and those made with the artificial mastoid.

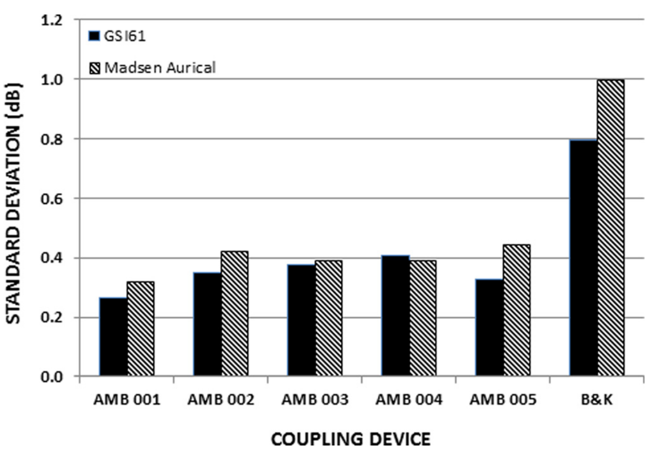

FIG. 3. (Color online) Standard deviations of repeated measurements made over five days for two audiometers on five AMBONE couplers and a B&K Type 4930 Artificial Mastoid. Each value is the average standard deviation across the nine test frequencies.

The data in Fig. 5 show a range of values that varied from mean ± 0.8 dB to mean ± 2.2 dB for the nine test frequencies. The average standard deviation across frequencies

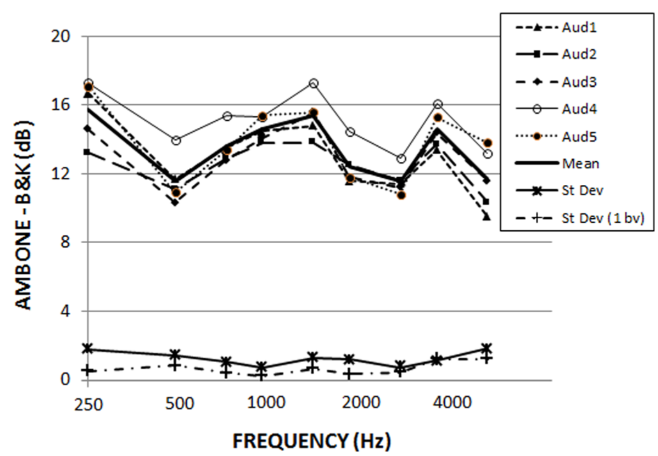

FIG. 5. (Color online) Differences between measurements made with AMBONE and measurements made with the B&K 4930 Artificial Mastoid for five audiometers and their associated bone vibrators. Also shown are the average standard deviations for measurements made with five audiometers and the same bone vibrator [standard deviation (1 bv)]. AMBONE levels are sound pressure levels in dB re 20 μPa. B&K levels are force levels in dB re 1 μN.

is 1.2 dB. Because these are difference values, the variance of the differences is equal to the sum of the variances of the two measurements that constitute the differences. The average standard deviation of 1.2 dB is roughly equal to the sum of the standard deviations for AMBONE and B&K 4930 measurements shown in Fig. 2. Because the B&K 4930 measurements have a larger standard deviation than the AMBONE measurements, the variability of the B&K 4930 measurements dominates the variability of the differences.

Also shown in Fig. 5 are the average standard deviations for five audiometers each activating the same bone vibrator (see + symbols). This permits an examination of the extent to which the variance is associated with the vibrator as opposed to the audiometer. The standard deviations across frequency were smaller when one vibrator was used. The average standard deviation across all frequencies with one vibrator was 0.7 dB. The lower standard deviation when one vibrator was used suggests that a significant portion of the variance associated with multiple audiometers is attributable to the bone vibrator.

From the data in Fig. 5 and the reference equivalent threshold force levels from the audiometer standards (ANSI S3.6-2010; ISO 389.3-1994) it is possible to calculate reference equivalent threshold sound pressure levels ($RETSPL_{bc}$) for calibration of audiometers with Radioear B-71 bone vibrators with the following formula:

$$RETSPL_{bc} = RETFL + D,$$

where RETFL is the reference equivalent threshold force level (dB re 1 μN) from the audiometer standards and D is the mean differences shown in Fig. 5 (solid bold line). That is, D is the numerical value of the difference between the sound pressure level (dB re 20 μPa) measured with AMBONE and the force level (dB re 1 μN) measured with the B&K 4930 Artificial Mastoid. $RETSPL_{bc}$ values were calculated for each of the five audiometers (see Fig. 6 and Table I).

To validate the $RETSPL_{bc}$ values in Table I, two audiometers were calibrated with AMBONE to those values. The output levels were then measured with a B&K artificial mastoid to determine the accuracy of calibration. The results, shown in Fig. 7, indicate that the audiometers calibrated with AMBONE were in calibration as determined by B&K 4930 measurements.

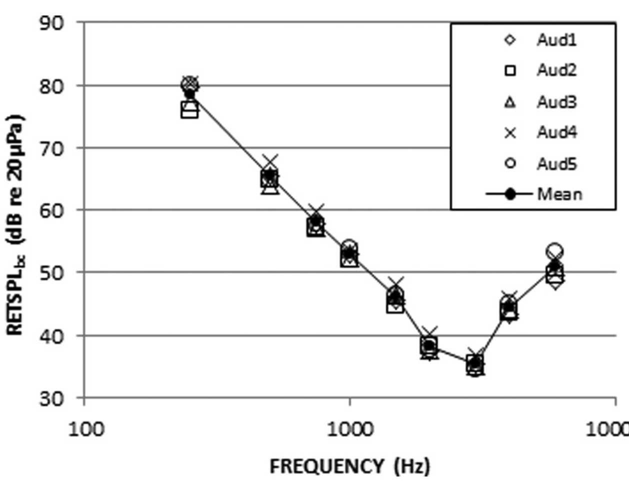

FIG. 6. Reference equivalent threshold sound pressure levels ($RETSPL_{bc}$) for bone conduction stimuli calculated from five audiometers (Aud1–Aud5).

TABLE I. Reference equivalent threshold sound pressure levels for bone conduction stimuli measured with AMBONE calculated for five audiometers.

	Frequency								
	250	500	750	1000	1500	2000	3000	4000	6000
Mean	78.6	65.4	57.9	52.9	46.2	38.2	35.4	44.4	51.0
St. Dev.	1.8	1.4	1.1	0.7	1.3	1.2	0.8	1.1	1.8

V. SUMMARY AND CONCLUSION

A device for calibration of audiometric bone-conduction vibrators is described which is based on a different principle than those in current use. Current artificial mastoids attempt to reproduce the mechanical impedance properties of the human head and provide measurements of force delivered to the head during bone conduction audiometry. AMBONE is a coupler that captures the acoustic radiation from the bone vibrator and enables measurements of the acoustic signal that can be related to the normal threshold of hearing for bone conduction. Measurements made with a variety of audiometers and bone vibrators indicate that AMBONE measurements are characterized by significantly lower variability than measurements made with the standard artificial mastoid. Reference equivalent threshold sound pressure levels for bone-conducted signals ($RETSPL_{bc}$) were derived.

Although the results presented here suggest a promising approach to bone-conduction calibration that could decrease cost and increase accuracy, the audiometer standards require the use of an artificial mastoid of which there is only one commercial product. The American audiometer standard (ANSI S3.6-2010, p. 31) states that "vibrators are calibrated using a mechanical coupler as specified in ANSI S3.13 or IEC 60318-6," which are the standards that specify the

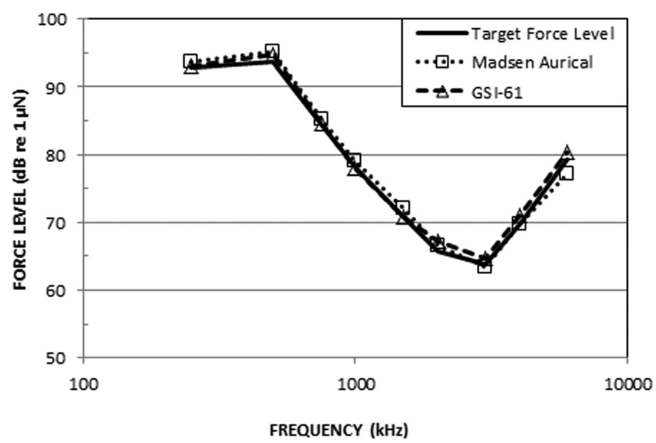

FIG. 7. Force levels measured with a B&K 4930 Artificial Mastoid for two audiometers that were previously calibrated with AMBONE to the mean $RETSPL_{bc}$ value in Table I. The solid line shows the target level ($RETSPL_{bc}$ + HL) where HL is the hearing level setting on the audiometer. HL values were 40 dB for all frequencies except 250 Hz where a 30 dB value was used.

characteristics of the mechanical artificial mastoid. The international audiometer standard (ISO 389-3, p. 3) has a similar requirement. Given the deliberate pace of standards committees, it may be a long time before other valid calibration methods are acknowledged in the standards.

A potential issue with the new method is that it relies on the acoustic radiation of the vibrator rather than the vibratory force itself to characterize the output. The use of an acoustic signal as a proxy for vibratory force has precedence in the Larson Davis AMC 493 device. While the direct measurement of the vibratory force seems intuitively preferable, it is important to recognize, as the international standard points out, that "the vibratory force developed by a bone vibrator is not, in general, the same on the coupler as on the person's mastoid" (IEC 60318-6, p. 5). Stated differently, the mechanical coupler does not accurately approximate the characteristics of the human head. Because the force level measured on the artificial mastoid is different from that delivered to the head, there is no advantage of measuring force levels. The critical feature is that the coupler measurement, whether mechanical or acoustic, can be related to normal hearing sensitivity in a consistent and reliable manner.

Another potential issue is the dependence on a "byproduct" or an "artifact," that is, the acoustic radiation of a device intended for mechanical stimulation. In the event that bone vibrators become available that have no acoustic radiation, the method may not be useful for those devices. However, it is probably inevitable that a mechanical device that vibrates in the audio range of frequencies will produce an acoustic radiation that is closely related to the mechanical output.

ACKNOWLEDGMENTS

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