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Comparisons among SPLs in Real Ears, 2 cm^3 and 6 cm^3 Couplers

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Abstract

Sound pressure levels (SPLs) were measured in the ear canals of 30 adult subjects with standard audiometric earphones (TDH-39) and insert earphones (Etymotic ER-3A) and compared to those generated in 2 cm^3 and 6 cm^3 couplers. Transfer functions are shown for real ear to 2 cm^3 coupler, real ear to 6 cm^3 coupler, 6 cm^3 to 2 cm^3 coupler, and dB HL under standard earphones to 2 cm^3 coupler SPL. In general, the data agreed rather well with published transfer functions that in most cases were derived by adding together a series of partial transfer functions from various studies. The conversion values from dB HL to 2 cm^3 coupler SPL could be useful in selection of certain hearing aid parameters, but the intersubject variability may limit their usefulness somewhat.

Key Words: Hearing aids, real-ear SPLs, couplers, correction factors, probe tube microphone measurements

Prior to selecting a hearing aid, most audiologists complete a standard audiologic evaluation. This typically includes the measurement of pure-tone thresholds, word recognition ability, most comfortable loudness levels (MCLs), and loudness discomfort levels (LDLs). These data are used to determine the appropriate electroacoustic characteristics for a hearing aid. This hearing aid selection decision may take several forms. The audiologist may utilize one of several hearing aid prescription schemes, such as the modified National Acoustics Laboratories of Australia (NAL) procedure (Byrne and Dillon, 1986), Prescription of Gain and Output (POGO, McCandless and Lyregaard, 1983), Memphis State University procedure (Cox, 1988), 1/3-2/3 gain rule (Libby, 1986), or the Berger procedure (Berger et al, 1988) to determine the electroacoustic characteristics. Alternatively, some personally derived formula or approach for selecting hearing aid characteristics may be employed. Finally, the data may be sent to a hearing aid manufacturer, who assumes responsibility for the selection rather than the audiologist.

Regardless of the hearing aid selection approach, the data which serve as the basis for the selection are those gathered in the audiologic evaluation. These measurements are commonly obtained with standard audiometric earphones, such as the TDH-39, 49, or 50. The SPLs generated by these earphones are specified as output developed in an NBS-9A 6 cm^3 coupler (ANSI, 1969). In contrast, the electroacoustic characteristics of hearing aids are specified by examining their output in an HA-1 or HA-2 2 cm^3 coupler (ANSI S3.22, 1987). As a result, it is difficult to translate accurately an MCL or LDL acquired with a standard earphone, values specified in dB HL or SPL in a 6 cm^3 coupler, to a predicted MCL or LDL with a hearing aid, where values are specified in a 2 cm^3 coupler.

Procedures developed by Hawkins (1980), Cox (1981), Hawkins et al (1987), and Dillon et al (1984) have attempted to overcome this basic transducer-calibration problem in LDL measurement, but each requires special equipment and calibration. In her hearing aid prescription scheme, Cox (1988) recommended that signals be delivered via a hearing aid receiver that has

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been calibrated in a 2 cm^3 coupler. If that is not feasible, conversion factors are applied to standard earphone values to correct them to 2 cm^3 coupler values. These conversion factors have typically been derived by summing a series of partial transfer functions obtained from several different studies. For example, in Cox's procedure (1988) the SSPL90 can be selected by measuring the upper limit of comfortable loudness (ULCL) under standard earphones and applying corrections to obtain 2 cm^3 coupler output levels. To obtain the corrections, she measured the transfer function for an audiometric earphone in a 6 cm^3 coupler to the opening of the ear canal (Cox, 1986), then added Shaw's transfer function from the ear canal opening to the tympanic membrane (Shaw, 1974) modified by a peak frequency shift observed in seven of her subjects (Cox, 1986), and then added real ear/2 cm^3 difference values (Sachs and Burkhard, 1972).

Another recent attempt to develop theoretical conversion factors from dB HL under standard earphones to 2 cm^3 coupler values can be found in Bentler and Pavlovic (1989). Their approach involved several stages. In the first stage, the results from two derivation methods designed to produce a 6 cm^3 coupler to tympanic membrane transfer function were averaged. In one of the derivation methods, they determined the difference between the minimum audible pressure in the ear canal (MAP) and the minimum audible pressure in a 6 cm^3 coupler (MAPC). The MAP was derived by combining the monaural minimum audible field (MAF) with the free field to tympanic membrane transfer function from Shaw (1974). The MAF was derived by applying correction factors (French and Steinberg, 1942) to a binaural MAF. The second derivation method involved the addition of the 6 cm^3 coupler to ear canal entrance transfer function to the ear canal entrance to tympanic membrane transfer function using data from six different studies. The results from these two derivation methods of obtaining 6 cm^3 coupler to tympanic membrane transfer functions were averaged. The second stage involved adding the previously derived transfer function to the MAPC, resulting in the minimum audible pressure at the tympanic membrane (MAPTM). Finally, the MAPTM was decreased by the 2 cm^3 coupler to tympanic membrane transfer function from Sachs and Burkhard (1972). The end result of these various combinations should be the dB HL (with standard earphone) to 2 cm^3 coupler SPL correction.

In theory, the combination of these various transfer functions should be accurate. However, it is certainly not a direct measurement method and involves the combination of data from many studies with different methodology and often with small numbers of subjects.

The purpose of this study was to measure directly on a larger number of subjects the differences between the 6 cm^3 and 2 cm^3 coupler to tympanic membrane transfer function and to provide data on conversions from dB HL to 2 cm^3 SPL values. Such correction factors could be useful in specifying hearing aid characteristics, especially for in-the-ear hearing aids. In addition, the study was designed so that real ear/2 cm^3 differences could also be obtained, as well as real ear/6 cm^3 differences. These latter differences can be compared to, and serve to verify, similar studies which have used fewer subjects (e.g., Sachs and Burkhard, 1972; Larson et al, 1977; Cox, 1986). In addition, knowledge of these differences could prove useful in research and clinical applications in which knowledge of sound pressure levels in the ear canal is of interest.

METHOD

Subjects

Thirty adults, 25 females and 5 males, aged 23 to 56 served as subjects. Otoscopic examinations indicated no significant cerumen. Tympanometry suggested normal middle ear function (pressure peak between +30 and −75 daPa). Since hearing loss was not necessary for inclusion in or exclusion from the study, hearing sensitivity was not measured.

Procedure

A TDH-39 earphone mounted in an MX-41/AR cushion and an Etymotic ER-3A earphone with foam earplug served as the transducers in this study. Each was attached to the output of an audiometer. With the audiometer attenuator at 70 dB HL, the SPLs at 250, 500, 750, 1000, 1500, 2000, 3000, 4000, and 6000 Hz were measured in the appropriate couplers (NBS-9A 6 cm^3 coupler for the TDH-39 and a HA-1 2 cm^3 coupler for the ER-3A) before data were collected from each subject. These data provided the conversion factors for the audiometer dial reading to dB SPL for each transducer in their respective coupler.

Ear canal SPLs were measured with the probe tube microphone system from a Rastronics CCI-10/3. The loudspeaker of the CCI-10/3 was disconnected, and the tracking filter was centered over each test frequency. The regulating microphone was not functional, and the unit simply served as a probe microphone measuring device.

For measurements with both transducers the probe tube tip extended 20 mm past the opening of the ear canal. Given that the average length of the adult ear canal is 25 mm (Zemplenyi et al, 1985), this location should be approximately 5 mm from the tympanic membrane. Based on the data of Gilman and Dirks (1986), this location should yield measurements that are within 1 dB of that developed at the tympanic membrane through 6000 Hz. The probe tube was inserted through a small hole drilled in the foam earplug attached to the ER3-A. With the TDH-39 earphone the probe tube was simply inserted into the ear canal. Care was taken that the pressure of the MX-41/AR earphone cushion did not compress the probe tube.

The audiometer attenuator dial was adjusted at each frequency until 75 dB SPL was measured by the probe microphone in the ear canal. The audiometer attenuator dial reading required for 75 dB SPL was recorded at each frequency separately with each transducer. Combining these measurements with the calibration data for the transducers in their respective couplers, the following transfer functions were made possible: real ear to 2 cm^3 coupler, real ear to 6 cm^3 coupler, 6 cm^3 to 2 cm^3 coupler, and dB HL for a TDH-39 earphone to 2 cm^3 coupler SPL.

RESULTS AND DISCUSSION

Real Ear to 2 cm^3 Coupler

The mean real ear to 2 cm^3 coupler transfer function for the 30 subjects is shown as the solid line in Figure 1. The dotted lines represent $\pm$ 1 standard deviation. The ordinate is plotted in the traditional manner (real ear minus 2 cm^3 coupler), with positive values indicating the output was greater in the real ear than in the 2 cm^3 coupler. For frequencies above 500 Hz the SPL is greater in the real ear and generally increases with frequency, reaching a maxi-

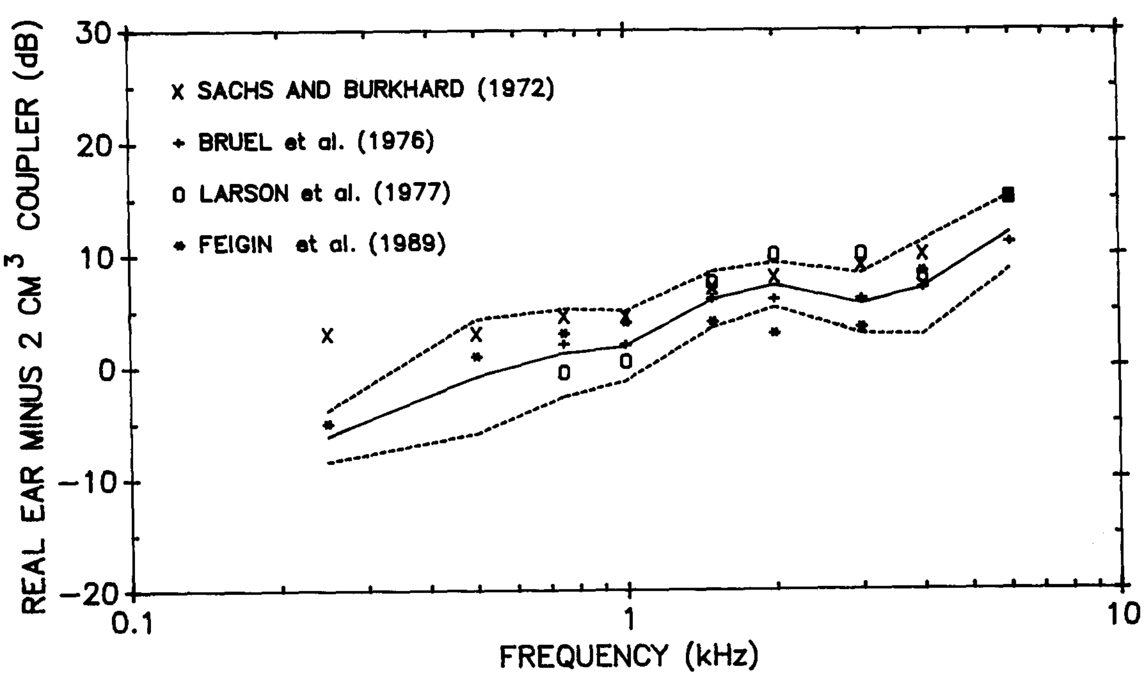

Figure 1 The real ear to 2 cm^3 coupler transfer function. The solid line represents the mean values for this study, and the dotted lines are $\pm$ 1 standard deviation. Values below zero indicate less SPL in the real ear than the 2 cm^3 coupler. Values above zero indicate more SPL in the real ear than the coupler. Results from four other studies are shown for comparison.

mum of 12 dB at 6000 Hz. Standard deviations across frequency ranged from 2 to 5 dB.

Results from several other studies investigating the relationship between SPL in the real ear and 2 cm^3 coupler are also shown in Figure 1. Included are data from Sachs and Burkhard (1972) for 11 subjects, Bruel et al (1976) for four subjects, Larson et al (1977) for 8 subjects (16 ears), and Feigin et al (1989) for 21 subjects. Interestingly, only the Feigin et al results represent uncorrected data. The other three studies made measurements significantly distant from the tympanic membrane that the data had to be corrected to predicted tympanic membrane values. These corrections were primarily made to values in the higher frequencies. The probe insertion depth in the Feigin et al study was 15 mm beyond the ear canal entrance, 5 mm less than that used in this study.

The agreement among these studies is rather close. With the exception of the Sachs and Burkhard data point at 250 Hz, the mean values from the other studies fall within or very close to ± 1 standard deviation of the mean for the present study. Only this study, Sachs and Burkhard, and Feigin et al present data for frequencies below 750 Hz. Slight leakage around the foam earmolds or probe tube hole with our subjects may account for the differences between our data and those of Sachs and Burkhard. Good agreement, however, is seen between the low-frequency data in this study and those of Feigin et al. Since both earmolds and custom in-the-ear hearing aids are rarely used with absolutely no leakage, our data may be a more accurate representation of differences between output in a real ear and a 2 cm^3 coupler than data obtained under conditions where an airtight seal is present.

Real Ear to 6 cm^3 Coupler

Figure 2 shows the real ear to 6 cm^3 coupler transfer function for a TDH-39 earphone. The solid line represents the mean data for the 30 subjects, and the dashed line is ± 1 standard deviation. There is less SPL in the real ear than in the 6 cm^3 coupler below 750 Hz, with the difference increasing as frequency decreases. The lower SPL in the low frequencies in the real ear is due to leakage around the MX-41/AR cushion, which does not occur in coupler measurements. There is a slight increase in real-ear SPL in the 1000 to 3000 Hz region, followed by a slight decrease in the higher frequencies. Stan-

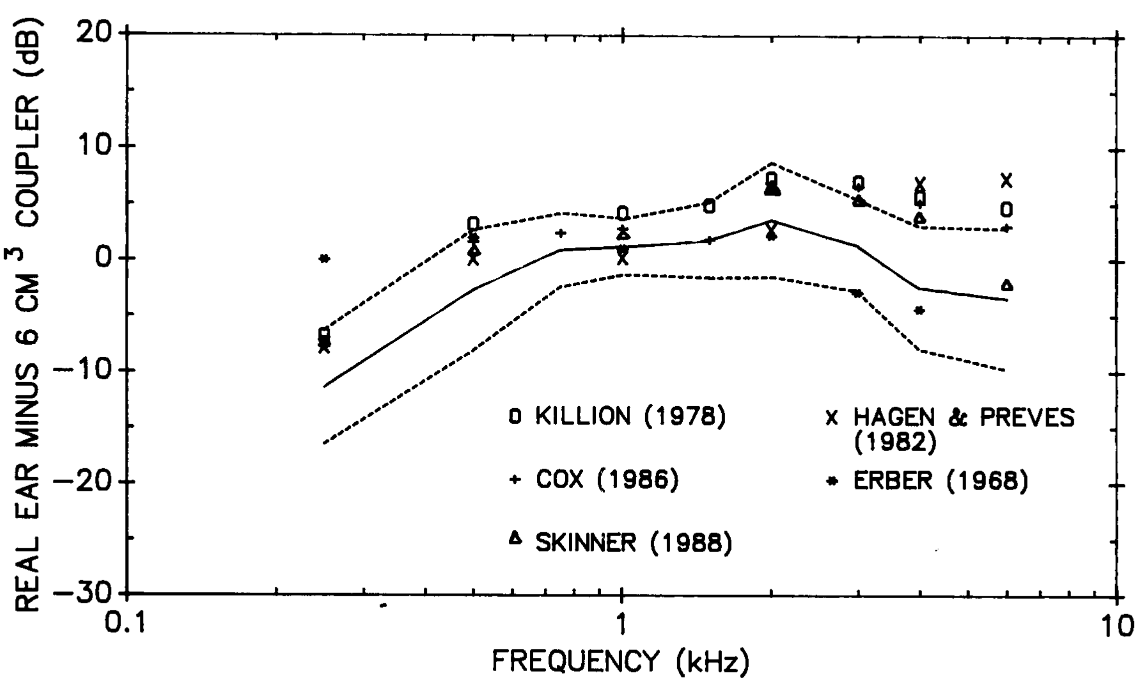

Figure 2 The real ear to 6 cm^3 coupler transfer function. The solid line represents the mean values for this study, and the dotted lines are ± 1 standard deviation. Values below zero indicate less SPL in the real ear than the 6 cm^3 coupler and values above zero indicate more SPL in the real ear than the coupler. Results from five other studies are shown for comparison.

dard deviations across frequency ranged from 2.5 to 6.7 dB.

Results from other studies on the real-ear response of an audiometric earphone are also shown in Figure 2. Data from Killion (1978) and Skinner (1988) are calculated transformations from other studies and values from calibration standards. Cox (1986), with ten subjects, and Hagen and Preves (1982) with nine subjects, measured the earphone response at the entrance to the ear canal with a probe tube microphone system and then transformed their data to the tympanic membrane with corrections from Shaw (1974). Erber (1968) used 30 subjects and measured the output of an earphone with a probe tube microphone located at an unspecified position in the ear canal.

The agreement is rather good through 2000 Hz across all of the studies. Above 3000 Hz, only the present study, Erber (1968), and Skinner (1988) show less SPL in the real ear than in the coupler. The present study found 2.5 dB less in the real ear than the coupler at 4000 Hz and 3.5 dB less at 6000 Hz. The results from Killion (1978), Hagen and Preves (1982), and Cox (1986) all indicate approximately 5 dB more in the real ear than the 6 cm^3 coupler in the 3000 to 6000 Hz region. The reason for the discrepancy is not clear. It is interesting, however, that the two sets of data (the present study and Erber) that show less SPL in the real ear than in the 6 cm^3 coupler at 4000 and 6000 Hz are those in which measurements were made in the ear canal. One explanation might be that in these two studies the probe tube was not close enough to the tympanic membrane, resulting in inaccurate measurements in the higher frequencies (Gilman and Dirks, 1986). While this is a possibility in Erber's study, as the location of the probe tube in the ear canal was not reported, it does not explain our data for two reasons. First, our probe tube placement (within 5 mm of the tympanic membrane for the average adult subject) should have produced values that were accurate within 1 dB through 6000 Hz (Gilman and Dirks, 1986). Second, the results from the first comparison (real ear versus 2 cm^3) showed rather good agreement with other studies in which transformations to the tympanic membrane location were made. If our probe tube were too distant from the tympanic membrane, the real ear/2 cm^3 coupler difference should also have been decreased in the higher frequencies compared to the other studies. The alternative explanation is that placement of the earphone cushion on the side of the head caused an outward movement of the probe tube. Care was taken with each subject, however, to ensure that this did not occur. Based upon these observations, it is tempting to conclude that the results from the present study may better represent the real-ear response of the audiometric earphone than data from previous studies.

6 cm^3 to 2 cm^3 Coupler

Figure 3 shows the difference between the output in a 6 cm^3 and 2 cm^3 coupler for the same SPL in the ear canal. All mean values are above zero, indicating that more SPL is measured in the 6 cm^3 than 2 cm^3 coupler for the same ear canal SPL. The mean differences range from 1 to 16 dB, with the greatest differences being observed in the higher frequencies. These data could be useful in converting 6 cm^3 coupler SPL values to comparable levels in a 2 cm^3 coupler. For instance, if a LDL were obtained under standard audiometric earphones and the audiologist or hearing aid manufacturer wished to convert the value to 2 cm^3 coupler SPL for purposes of specifying the SSPL90 of a hearing aid, these differences could be applied to the 6 cm^3 coupler values. Since most audiologists work in dB HL, these values were converted to provide the next transform, dB HL with TDH-39 earphones to 2 cm^3 coupler SPLs.

dB HL to 2 cm^3 Coupler

Table 1 shows the conversion factors from dB HL to the 2 cm^3 coupler SPL based on the data from this study. These values assume the audiometer is calibrated precisely to the ANSI standard, and the TDH-39 earphone is mounted in an MX-41/AR cushion. This table could be used in the following manner. If an LDL of 100 dB HL was obtained at 1000 Hz, 5.5 dB would be added to 100 to yield an LDL of 105.5 dB in a 2 cm^3 coupler, a value appropriate for selecting SSPL90. In a similar way, thresholds or MCLs in dB HL could be converted to 2 cm^3 coupler SPL values.

The appropriate conversions are also shown for the TDH-49 and 50P earphone. These values were obtained by adding the calibration differences for the TDH-39 and TDH-49/50P earphone to the conversion factors derived in this study. All of the differences are less than 2 dB.

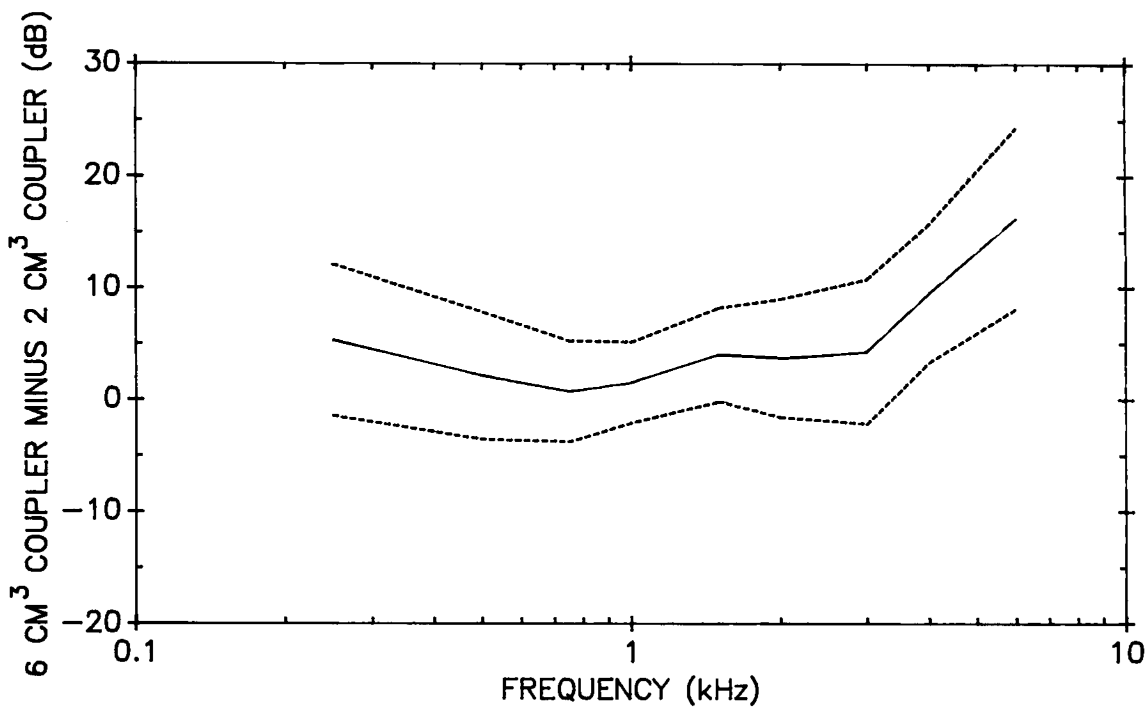

Figure 3 The 6 cm³ to 2 cm³ coupler transfer function. The solid line represents the mean values for this study, and the dotted lines are ± 1 standard deviation. Values above zero indicate more SPL in the 6 cm³ than the 2 cm³ coupler for the same real-ear SPL.

The theoretical calculations of the dB HL to 2 cm³ coupler differences determined by Bentler and Pavlovic (1989) and Skinner (1988) are also shown in Table 1. Both of these studies arrived at conversion factors by combining various transfer functions and calibration standards. With the exception of 250 Hz, the differences between the measured values from this study and the derived values of the Bentler and Pavlovic and Skinner studies are less than 3 dB. At 250 Hz the conversion value from dB HL to 2 cm³ coupler from the present study is 8.5 and 5.7 dB greater than those derived in the other two studies. This difference may be due to leaks around the foam earplugs or probe tube in the real-ear measurements, a possibility discussed earlier.

One purpose of this study was to determine correction factors to use as an alternative to 6 cm³ coupler values to select 2 cm³ coupler hearing aid characteristics. It is also useful to examine the magnitude of error involved if one took dB HL values and converted them to SPL by adding the ANSI norms. In other words, what is the error if one makes the assumption that output in a 6 cm³ coupler is equivalent to out-

Table 1 Conversion Values from dB HL (ANSI, 1969) to dB SPL in a 2 cm³ Coupler

Study	*Frequency (kHz)*								
	.25	*.5*	*.75*	*1*	*1.5*	*2*	*3*	*4*	*6*
Present Study (TDH-39)	20.7	9.9	7.3	5.5	2.5	5.2	5.7	−.5	−.2
Present Study (For TDH-49)	21.7	11.9	7.8	6.0	3.5	7.2	5.2	.5	−2.2
Bentler and Pavlovic (1989) (TDH-39 and 49)	12.2	7.5	5.4	4.3	4.6	7.9	4.6	1.2	2.2
Skinner (1988) (TDH-39)	15.0	8.0	–	4.0	–	7.0	6.0	1.0	−1.0

Table 2 Potential Error (dB) if Assumption Is Made that 6 cm³ Coupler SPL Is Equal to 2 cm³ Coupler SPL. All Values Indicate More SPL in 6 cm³ than 2 cm³ Coupler for Same Real-Ear SPL

Frequency (kHz)								
.25	.5	.75	1	1.5	2	3	4	6
4.8	1.6	0.7	1.5	3.9	3.8	4.3	10.0	15.7

put in a 2 cm³ coupler? Table 2 shows the potential error if this common assumption is made. The errors range from less than 1 dB to 15.7 dB. All differences are positive, indicating that higher SPLs would be suggested when a simple dB HL to 6 cm³ coupler conversion is made instead of dB HL to 2 cm³ coupler. Applying these errors to an SSPL90 selection from LDLs, the consequence might be "overfitting" or a higher SSPL90 than necessary. However, the error falls within plus or minus one standard deviation of our mean data from 250 to 3000 Hz.

The standard deviations of the conversion factors from dB HL to 2 cm³ coupler SPL provide insight into the use of these mean conversion factors for predicting 2 cm³ coupler values for a given person. Table 3 shows the standard deviations at each of the test frequencies for our 30 subjects. They range from 3.6 dB at 1000 Hz to 8.1 dB at 6000 Hz. These values provide information on the accuracy that can be expected when predictions are made for a given individual based on these mean data. As an example, for 95 percent of individuals the derived 2 cm³ coupler SPL suggested from the dB HL reading at 1000 Hz would be within 7.2 dB of the actual value. The worst case is at 6000 Hz, where the derived value would be within 16.2 dB for 95 percent of individuals.

The conversions in Table 1, while providing useful information, are clearly limited by the observed variability across subjects. Such variability would make the application of mean data-based conversions to the fitting of individual hearing aids somewhat tenuous. If the conversion from dB HL to 2 cm³ coupler is the one of interest, the problem can be minimized by using the procedures of Hawkins (1980) or Cox (1981), mentioned earlier, or by using commercially available transducers that are calibrated in a 2 cm³ coupler, such as the Etymotic ER series earphones. The threshold, MCL, or LDL measurements are then in the correct units. One does not have to rely on mean conversion factors where intersubject variability can be substantial. Until use of transducers such as these becomes widespread, however, conversions for standard audiometric earphones may prove useful.

Table 3 Standard Deviations (in dB) for the dB HL to 2 cm³ Coupler SPL Conversions for the 30 Subjects in This Study

Frequency (kHz)								
.25	.5	.75	1	1.5	2	3	4	6
6.5	6.6	4.5	3.6	4.2	5.3	6.5	6.1	8.1

It was emphasized earlier that much of the existing data concerning the various transfer functions covered in this study had been derived by adding together a series of partial transfer functions. It is interesting that those data agree rather well with ours, in which we measured the entire function. It seems that the whole may indeed equal the sum of the parts.

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