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The Effect of Tubing Length and Coupling Method on Real-Ear to Coupler Differences and Hearing Threshold Measurements

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Abstract

Purpose: This article demonstrates the effects of tubing length and coupling type (foam tip or personal earmold) on hearing threshold and real-ear-to-coupler difference (RECD) measures.

Method: Behavioral thresholds from 0.25 through 8 kHz are reported at various tubing lengths for twenty-eight normal-hearing adults between the ages of 22 and 31 years. RECD values are also reported for 14 of the participants. All measures were made with an insert earphone coupled to a standard foam tip and to each participant's personal earmold.

Results: Threshold and RECD measures completed with a personal earmold were significantly different from those obtained with a foam tip on repeated-measures analyses of variance. One-sample t-tests showed these differences to vary systematically with increasing tubing length, with the largest average differences (7-8 dB) occurring at 4 kHz.

Conclusions: This systematic examination demonstrates the equal and opposite effects of tubing length on acoustic and behavioral measures. Specifically, as tubing length increases, sound pressure level in the ear canal decreases, affecting both hearing thresholds and the real-ear portion of the RECDs. This demonstration shows that when the same coupling method is used to obtain the RECD and hearing thresholds, equal and accurate estimates of real-ear sound pressure level are obtained.

The use of real-ear measures is the preferred method for verifying hearing-aid fittings because they allow for the measurement of hearing-aid output near the tympanic membrane. In this way, the unique characteristics of a patient's ear canal may be taken into account to ensure that speech is audible and that hearing-aid output matches prescribed targets. Real-ear measures are commonly performed by placing a probe microphone near the tympanic membrane and measuring sound pressure level across frequency with a hearing-aid analyzer. Verification of and adjustments to hearing-aid output can be made in real time with the use of these systems.

To compare hearing-aid performance in the ear to hearing thresholds on one graphic display, it is necessary to convert the patient's hearing threshold levels from decibels of hearing level (dB HL) to decibels of sound pressure level (dB SPL), as measured at the plane of the probe microphone. Modern hearing-aid analyzers use individually measured or stored average values to make this conversion through a series of steps represented in Figure 1. The steps are similar to those of Revit's (1997) Circle of Decibels but arranged in a triangular fashion. In this configuration, the points of the triangle represent measured levels (e.g., dB HL), whereas the sides of the triangle represent calculated transforms required to convert one measured value to another. A sound level meter is substituted for a hearing-aid analyzer in this illustration and, as shown, levels may be transformed either in a clockwise or counter-clockwise direction. Going counter-clockwise, a hearing threshold level can be converted from dB HL (Dial) to dB SPL near the tympanic membrane (Real Ear) by adding the real-ear-to-dial-difference (REDD). One method of obtaining the REDD is by delivering a signal from the audiometer through an earphone at a specified level (e.g., 70 dB HL), measuring the SPL of that signal with a probe microphone near the tympanic membrane, and then subtracting the dial value from the real-ear value. Once this transform is obtained, it can be used to convert any given HL to SPL near the tympanic membrane and vice versa. Although it is the most direct route from the audiometer to the real ear, it is impractical to obtain these measures in a busy clinical setting, particularly with patients who are unable or unwilling to sit for prolonged probe-microphone measures.

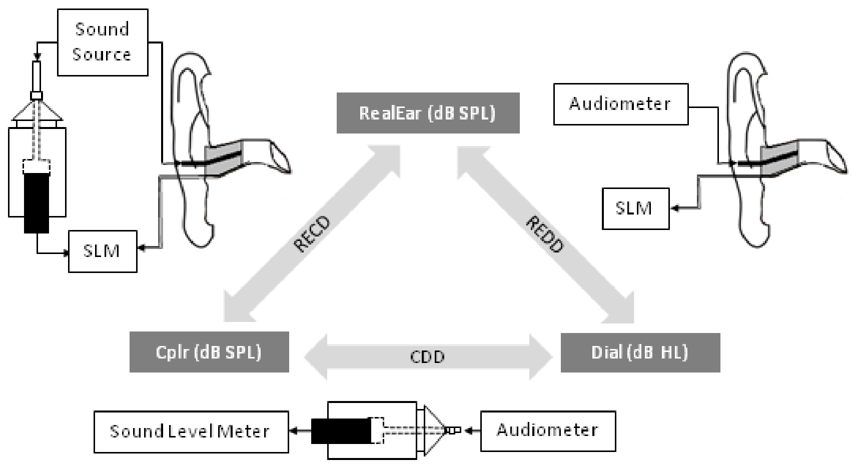

Figure 1. The relation between measured values and transforms. The points of the triangle represent measured levels and the sides of the triangle represent the transforms necessary to convert from one level to another.

The clockwise route is less direct but more easily incorporated into the hearing-aid verification process. Two transforms are required. The first is called the coupler-to-dial difference (CDD), which is a transform from dB HL to dB SPL measured in an acoustic coupler. It is obtained by delivering a signal generated by an audiometer via an earphone into an acoustic coupler at a specific level, measuring the SPL of the signal developed in the acoustic coupler, and then calculating the difference between the level measured in the acoustic coupler and the dial value.[1] When the CDD transform is added to any Dial value, the sum is the dB SPL that

[1] These values are specific to the transducer and coupler used during testing. Supra-aural earphones require a 6-cm^3 coupler whereas insert earphones require a 2-cm^3 coupler. Hereafter, the term “transducer” will refer to an insert earphone and the term “acoustic coupler” will refer to a 2-cm^3 coupler with rigid tube, also referred to as an HA2 coupler.

would be measured in an acoustic coupler. If the audiometer is calibrated to American National Standards Institute (ANSI S3.6-2010) standards, it is acceptable to use the ANSI Reference Equivalent Threshold SPL instead of the CDD, which is the more clinically popular method to make this conversion. The second transform required for this route is the real-ear-to-coupler difference (RECD). It is obtained by calculating the difference between the measured SPL of a given signal in the ear canal of the patient and in the acoustic coupler [see Moodie, Seewald, and Sinclair (1994) for a recommended clinical procedure].

An advantage of the clockwise route (Dial + CDD + RECD = Real Ear SPL) is that it is faster and easier to use than the counter-clockwise route (Munro & Davis, 2003). This is of particular importance in a clinic setting, particularly with pediatric patients (Munro & Hatton, 2000; Seewald, Moodie, Sinclair, & Scollie, 1999). Where the CDD and REDD are obtained by measuring the level of individual pure-tone stimuli, the RECD can be obtained quickly with swept pure tones, an impulse tone, or a broad band noise, reducing the time spent measuring the real-ear component of this transform. Also, the acoustic coupler used to obtain the RECD is the same one used to measure hearing-aid performance in the test chamber of a hearing-aid analyzer. When the RECD is applied to acoustic-coupler measures of hearing-aid output, very close estimates of real-ear performance can be made (Seewald et al, 1999). The use of this method is ideal for presetting hearing aids with advanced technology or multiple programs as well as for fitting hearing aids on young children who are less likely to tolerate real-ear measures (Munro & Davis, 2003; Munro & Hatton, 2000; Scollie, Seewald, Cornelisse, & Jenstad, 1998; Seewald et al, 1999).

The accuracy of this method, however, may be reduced when inconsistent methods are used to obtain the measured values. Note that in Figure 1, the transducer is coupled to the ear with a standard foam tip for both the RECD and the hearing levels. A variation on this technique, as recommended by Moodie et al, (1994), includes the use of a standard foam tip to obtain hearing thresholds and the patient's personal earmold to obtain the RECD. Although these coupling methods differ in the amount of acoustic leakage, depth of insertion, and length of the sound bore (Munro, 2004), the primary difference is the length of the tubing, which may cause significant variation in measures of real ear SPL (Bagatto, Scollie, Seewald, Moodie, & Hoover, 2002; Munro & Buttfield, 2005; Munro & Salisbury, 2002). The purpose of this exercise was to demonstrate more fully the effect of tubing length on hearing threshold and RECD measures. By quantifying the effects of tubing length directly, a precise estimate of the error imposed on the hearing-aid fitting is revealed.

Method

Participants

Behavioral thresholds were obtained from 28 adults (8 males, 20 females) with normal hearing between the ages of 22 and 31 years of age (*M* = 24.46, *SD* = 2.13). Because real-ear measures were less variable than the behavioral measures, they were only obtained from 14 of the original 28 adults (6 males, 9 females) who were between the ages of 23 and 28 years (*M* = 24.86, *SD* = 1.7). All participants were audiology graduate students who owned at least one custom acrylic earmold. All participants had normal peak static acoustic admittance and peak pressure as measured by tympanometry (Wiley, Oviatt, & Block, 1987). Informed consent was obtained for all participants according to the procedures required by the Institutional Review Board at Arizona State University. Testing was completed in a single session lasting no longer than 75 minutes.

Experimental task

Behavioral thresholds. Pure tone thresholds were obtained with a clinical audiometer (GSI 61) for octave and inter-octave frequencies from 250 through 8 kHz using 1 dB step-sizes in a 1-up, 3-down, bracketing procedure. Threshold was determined to be the lowest level at which a pulsed pure tone could be detected in 2 of 3 ascending trials. This search procedure corresponds to 50% on the psychometric function (Levitt, 1971). The insert earphone (Etymotic, ER 3A) was coupled to the listener's personal earmold at each of four tubing lengths (3, 4, 5, & 6 cm). The same type of tubing (13 medium, Westone Laboratories, Inc., USA), marked in 1 cm increments, was used for each earmold. Earmold tube length was systematically decreased from 6 to 3 cm in 1 cm increments after each threshold procedure. Once the earmold was placed in the subject's ear, it was not removed until testing was completed. The insert earphone was then coupled to a standard foam tip (2.5 cm tubing length). No order effects were expected; therefore, the conditions were not counterbalanced. All testing was conducted in a double-walled, sound-treated booth meeting ANSI specifications for ambient noise (ANSI, 2003). The audiometer was calibrated according to ANSI standards (ANSI, 2004) with output within .3 dB of expected values down to 0 dB dial settings.

Real-ear-to-coupler differences. Real-ear SPL was measured for each test frequency using a probe microphone system (Etymotic, ER-7C). Coupler measures were obtained using the HA2 coupler recommended by the probe-microphone manufacturer (Bruel & Kjaer, DB-0138). Test signals were 2,000 ms pure tones generated by custom laboratory software, which were routed through a clinical audiometer (GSI 61) and presented at 70 dB HL using ER-3A insert earphones. Using the constant insertion depth method (Hawkins, Alvarez, & Houlihan, 1991), the probe-tube was placed in the canal at a depth of approximately 28 mm as referenced to the listener's intertragal notch. Once the earmold and probe tube were placed in the ear, they were not removed until all testing was completed to prevent variations in probe-tube placement. RECDs were calculated at each test frequency in each condition by subtracting the SPL measured in the acoustic coupler from the Real-Ear SPL measured in the ear canal. Because individual subject differences between foam tip and earmold measures were used in this study, the acoustic effects of tubing length would be unaffected by the variability associated with differences in real-ear SPL across subjects.

Results and Discussion

Table 1 shows the average (and 1 SD) audiometric thresholds in dB HL as a function of test frequency for each of the five coupling conditions. On average, hearing thresholds were <10 dB HL at all test frequencies and at all coupling/tubing length conditions. Variation about the mean (4-6 dB) was also similar across frequency with slightly higher variation at 8 kHz (7-9 dB). As for tubing length effects, hearing thresholds increased (became poorer) at 3 and 4 kHz as tubing length increased. As expected, the effect of tubing length on the behavioral thresholds is directly related to changes to the acoustic signal in the ear canal. Table 2 shows the average (and SD) signal level in the ear canal as a function of frequency for the coupler, foam tip, and each length of tubing. With the exception of 250 Hz, the SPL measured with the foam tip and the personal earmold was greater than the SPL measured in the coupler. Table 3 shows the average RECD values in dB (and 1 SD) as a function of test frequency for each of the five coupling conditions. On average, RECDs were <10 dB at all test frequencies and at all coupling/tubing lengths with the exception of 8 kHz. Working from left to right, RECDs with the foam tip were generally smaller at low frequencies, growing larger as frequency increased. Variation about the average also increased with frequency. As for measures obtained with the earmold, RECDs increased (became larger) at mid frequencies (1 and 1.5 kHz) but decreased at high (3 and 4 kHz) and low (.25 kHz) frequencies.

Table 1. Average threshold values (1 SD) in dB HL at octave and inter-octave frequencies for foam tip and participant's personal earmold at each length of tubing.

	Frequency (kHz)									
	0.25	0.5	0.75	1	1.5	2	3	4	6	8
Foam Tip	3 (5)	2 (5)	2 (5)	3 (4)	3 (5)	4 (6)	4 (5)	0 (5)	-1 (6)	1 (9)
Earmold 3cm	7 (5)	3 (5)	2 (5)	2 (5)	2 (5)	3 (5)	4 (5)	2 (5)	2 (6)	-1 (8)
Earmold 4cm	7 (5)	3 (4)	1 (5)	2 (6)	1 (4)	2 (5)	6 (5)	5 (6)	1 (6)	-1 (7)
Earmold 5cm	8 (4)	3 (5)	2 (5)	1 (5)	0 (5)	2 (5)	8 (5)	7 (6)	1 (6)	1 (8)
Earmold 6cm	8 (5)	3 (5)	1 (5)	1 (4)	-1 (4)	3 (5)	9 (5)	7 (5)	4 (6)	-1 (8)

Table 2. Average signal level (and 1 SD) in the ear canal as a function of frequency for the coupler, foam tip, and each length of tubing.

	Frequency (Hz)									
	250	500	750	1000	1500	2000	3000	4000	6000	8000
Coupler	79.53	78.73	80.37	80.84	82.76	84.52	83.57	76.26	59.5	43.51
Foam	81.0 (2.1)	80.8 (2.8)	83.7 (3.3)	84.9 (3.1)	88.1 (1.7)	89.6 (2.5)	89.5 (4.3)	85.3 (5.5)	66.2 (8.6)	57.3 (11.0)
3cm	76.1 (4.6)	80.0 (2.4)	84.2 (2.3)	85.9 (2.0)	88.9 (2.5)	90.2 (2.3)	88.2 (2.8)	79.6 (8.6)	62.6 (3.2)	55.5 (6.1)
4cm	75.9 (3.9)	80.1 (2.0)	84.3 (2.0)	86.4 (1.9)	90.1 (1.7)	91.5 (2.0)	86.7 (3.2)	78.5 (3.4)	65.2 (3.1)	55.6 (3.8)
5cm	74.7 (4.7)	79.8 (2.5)	84.3 (2.2)	87.0 (2.1)	91.5 (1.8)	91.4 (4.1)	84.3 (3.4)	77.1 (3.4)	65.9 (3.8)	53.9 (6.5)
6cm	73.2 (5.3)	79.7 (2.9)	84.7 (2.1)	88.0 (2.0)	92.0 (1.8)	91.4 (2.8)	82.9 (3.4)	78.6 (3.3)	61.6 (3.6)	55.7 (6.3)

Table 3. Average RECD values (1 SD) in dB HL at octave and inter-octave frequencies for foam-tip and participant's personal earmold at each length of tubing.

	Frequency (kHz)									
	0.25	0.5	0.75	1	1.5	2	3	4	6	8
Foam Tip	1 (2)	2 (3)	3 (3)	4 (3)	5 (2)	5 (3)	6 (4)	9 (5)	6 (8)	14 (10)
Earmold 3cm	-4 (4)	1 (2)	4 (2)	5 (2)	6 (3)	6 (2)	5 (3)	4 (9)	3 (5)	12 (6)
Earmold 4cm	-4 (4)	1 (2)	4 (2)	5 (2)	7 (2)	7 (2)	3 (3)	2 (3)	5 (5)	12 (6)
Earmold 5cm	-5 (5)	1 (2)	4 (2)	6 (2)	9 (2)	7 (4)	1 (3)	1 (3)	6 (5)	11 (6)
Earmold 6cm	-7 (5)	1 (3)	4 (2)	7 (2)	9 (2)	7 (3)	-1 (3)	2 (3)	2 (5)	12 (6)

Two repeated-measures analyses of variance were conducted using frequency and tubing length as within-subjects factors to identify significant changes in threshold and RECD difference measures. All measured values were relative to those obtained with the foam tip (i.e., earmold – foam tip). Because of significant findings on Mauchly's sphericity test, the *F*-tests were modified using the Greenhouse-Geisser correction for this and all subsequent ANOVAs. All analyses were appraised using a significance level of $p<0.05$ unless otherwise noted. Results for the threshold measures revealed significant main effects of tubing length (F (2.504, 67.606) = 8.852; $p < .001$, $\eta^2_p = .247$) and frequency (F (4.080, 110.162) = 20.748; $p < .001$, $\eta^2_p = .435$), as well as a significant tubing length x frequency interaction (F (11.659, 314.795) = 15.579; $p < .001$, $\eta^2_p = .366$). The same main effects of tubing length (F (1.768, 21.216) = 8.277; $p = .003$, $\eta^2_p = .408$) and frequency (F (2.135, 25.625) = 7.379; $p = .003$, $\eta^2_p = .381$) were observed for the RECD measures as well as a significant tubing length x frequency interaction (F (3.814, 45.765) = 20.150; $p < .001$, $\eta^2_p = .627$).

Post-hoc pairwise comparisons with a Bonferroni adjustment for multiple comparisons of tubing length revealed mean threshold differences between the 3 and 4 cm tubing lengths to be significantly different than 5 and 6 cm tubing lengths. For RECD differences, values obtained with 3 cm tubing were found to be significantly different from those obtained with 5 and 6 cm tubing. One-sample t-tests (with a Bonferroni adjustment for multiple comparisons, $p<0.005$) were used to examine the effect of tubing length at each test frequency for average threshold and RECD values. Because the values used in the statistical analyses were relative to the foam tip measures, values obtained using the foam tip were the reference (zero) for the t-test. Results of these analyses are displayed in Tables 4 and 5 for threshold and RECD values, respectively. Threshold values obtained with earmolds were significantly different from those obtained with the foam tip at one or more frequency for all lengths of tubing (indicated in bold). The significant differences at 250 Hz for all tubing lengths suggest the presence of slit-leaks around the earmold. Subsequently, results for this frequency were omitted from further discussion. The remaining results indicate consistent effects on hearing threshold at and around 4 kHz for all tubing lengths with similar effects for RECD measures for tubing lengths >3cm.

Table 4. One-sample t-tests of changes in hearing thresholds as a function of frequency for each tubing length.

3cm

Hz	*t*	*df*	*p* (2-tailed)	95% Confidence Interval Lower	Upper
250	4.477	27	**.000**	1.95	5.26
500	.434	27	.668	-.80	1.23
750	.416	27	.681	-.84	1.27
1000	-1.616	27	.118	-2.51	.30
1500	-.722	27	.477	-1.78	.86
2000	-.730	27	.472	-1.63	.78
3000	.067	27	.947	-1.06	1.13
4000	3.125	27	**.004**	.58	2.78
6000	4.737	27	**.000**	1.74	4.40
8000	-2.304	27	.029	-4.66	-.27

4cm

Hz	*t*	df	*p* (2-tailed)	95% Confidence Interval Lower	Upper
250	5.747	27	**.000**	2.92	6.16
500	.889	27	.382	-.79	2.01
750	-1.055	27	.301	-1.58	.51
1000	-1.783	27	.086	-3.23	.23
1500	-2.414	27	.023	-3.24	-.26
2000	-2.141	27	.041	-2.03	-.04
3000	3.004	27	.006	.50	2.64
4000	6.639	27	**.000**	3.38	6.41
6000	2.719	27	.011	.43	3.07
8000	-2.614	27	.014	-4.97	-.60

5cm

Hz	*t*	*df*	*p* (2-tailed)	95% Confidence Interval Lower	Upper
250	7.605	27	**.000**	3.89	6.76
500	.634	27	.532	-.88	1.67
750	1.036	27	.309	-.66	2.02
1000	-2.654	27	.013	-3.23	-.41
1500	-3.218	27	**.003**	-4.21	-.93
2000	-3.554	27	**.001**	-3.10	-.83
3000	7.156	27	**.000**	2.80	5.06
4000	13.447	27	**.000**	5.96	8.11
6000	2.814	27	.009	.39	2.47
8000	-1.115	27	.275	-3.35	.99

6cm

Hz	*t*	*df*	*p* (2-tailed)	95% Confidence Interval Lower	Upper
250	7.636	27	**.000**	4.15	7.20
500	1.907	27	.067	-.09	2.37
750	-.855	27	.400	-1.82	.75
1000	-3.102	27	**.004**	-4.09	-.83
1500	-5.350	27	**.000**	-4.79	-2.14
2000	-1.694	27	.102	-2.13	.20
3000	7.131	27	**.000**	3.13	5.98
4000	12.354	27	**.000**	5.24	7.33
6000	6.653	27	**.000**	2.96	5.61
8000	-2.567	27	.016	-4.43	-.49

Table 5. One-sample t-tests of changes in RECD values as a function of frequency for each tubing length.

3cm

Hz	*t*	*df*	*p* (2-tailed)	95% Confidence Interval Lower	Upper
250	4.120	13	**.001**	2.38	7.62
500	1.000	13	.336	-.75	2.03
750	-1.375	13	.192	-1.47	.33
1000	-3.160	13	.008	-1.80	-.34
1500	-2.183	13	.048	-1.85	-.01
2000	-1.605	13	.133	-1.51	.22
3000	.940	13	.364	-1.30	3.30
4000	2.269	13	.041	.16	6.69
6000	1.704	13	.112	-1.01	8.59
8000	.686	13	.505	-3.69	7.11

4cm

Hz	*t*	*df*	*p* (2-tailed)	95% Confidence Interval Lower	Upper
250	4.755	13	**.000**	2.88	7.69
500	.962	13	.353	-.80	2.09
750	-1.260	13	.230	-1.55	.41
1000	-3.387	13	**.005**	-2.22	-.49
1500	-9.539	13	**.000**	-2.45	-1.55
2000	-4.881	13	**.000**	-2.58	-1.00
3000	2.335	13	.036	.20	5.09
4000	4.346	13	**.001**	3.59	10.69
6000	.582	13	.570	-3.48	6.05
8000	.614	13	.550	-3.78	6.78

5cm

Hz	*t*	*df*	*p* (2-tailed)	95% Confidence Interval Lower	Upper
250	4.946	13	**.000**	3.62	9.24
500	1.015	13	.328	-.97	2.68
750	-1.260	13	.230	-1.55	.41
1000	-5.292	13	**.000**	-2.82	-1.18
1500	-13.524	13	**.000**	-3.89	-2.82
2000	-6.395	13	**.000**	-3.44	-1.70
3000	4.467	13	**.001**	2.58	7.42
4000	4.974	13	**.000**	4.61	11.68
6000	.327	13	.749	-3.60	4.89
8000	1.645	13	.124	-1.10	8.10

6cm

Hz	*t*	*df*	*p* (2-tailed)	95% Confidence Interval Lower	Upper
250	5.608	13	**.000**	4.61	10.39
500	.757	13	.462	-1.19	2.48
750	-1.803	13	.095	-2.20	.20
1000	-9.611	13	**.000**	-3.94	-2.49
1500	-17.065	13	**.000**	-4.51	-3.49
2000	-2.852	13	.014	-2.39	-.33
3000	5.680	13	**.000**	3.90	8.68
4000	4.285	13	**.001**	3.36	10.21
6000	2.418	13	.031	.49	8.79
8000	.865	13	.404	-2.92	6.77

The top panel of Figure 2 shows the average threshold changes (relative to the thresholds obtained with the foam tip) in dB as a function of test frequency for each length of earmold tubing. Also shown are the average threshold changes and 95% confidence intervals collapsed across tubing length. Positive and negative values indicate that the threshold measured with the earmold was higher (poorer) or lower (better) than thresholds obtained with the foam tip, respectively. The bottom panel of Figure 2 shows average RECD differences between the coupling conditions using the same convention as the top panel. These values represent the RECD foam tip values subtracted from the RECD earmold values as a function of tubing length. Positive values indicate that the real-ear portion of the RECD obtained with the earmold was higher than the real-ear portion of the RECD obtained with the foam tip. Conversely, negative values indicate that the real-ear portion of the RECD obtained with the earmold was lower than that obtained with the foam tip. Also, note that the functions in the bottom panel are the inverse of those in the top panel at all frequencies except 8 kHz, indicating that the changes in threshold are the direct result of changes to the acoustic signal in the ear canal. For instance, the Real-Ear SPL at 1.5 kHz in the longest tubing condition resulted in an average hearing threshold that was nearly 4 dB less (better) than that derived with the foam tip. This earmold condition resulted in an RECD that was 4 dB higher than the RECD obtained with the foam tip at that same frequency. This inverse relationship can be observed across frequency and, depending on the length of tubing, the differences in RECD and hearing threshold values can be large. The non-inverse results at 8 kHz are likely due to standing waves in the ear canal that decreased measured RECD values at this frequency. Figure 3 shows the same average differences between earmold and foam tip plotted as a function of tubing length for threshold measures (top panel) and RECD values (bottom panel). Filled symbols indicate a significant difference between the earmold and foam tip measures. Differences varied systematically with increasing tubing length with the largest average difference of 7 and 8 dB occurring at 4 kHz for threshold and RECD values, respectively. Smaller changes in both hearing thresholds and RECD values (~5 dB range) were observed for the shortest tubing-length condition compared to a larger variation in hearing thresholds and RECD values (~10 dB range) observed for the longest tubing-length conditions. These differences suggest that patients having shorter tubing lengths are less likely to be affected by the different coupling methods. As an aside, the RECD transforms indicate that at no frequency was the SPL developed in the ear canal represented well by the acoustic coupler, except perhaps at 0.25, 0.5, and 2 kHz where the average difference was within 2 or 3 dB. Therefore, the need to account for the differences between the ear canal and the acoustic coupler is an important part of coupler-based hearing-aid fittings regardless of the tubing length of the earmold.

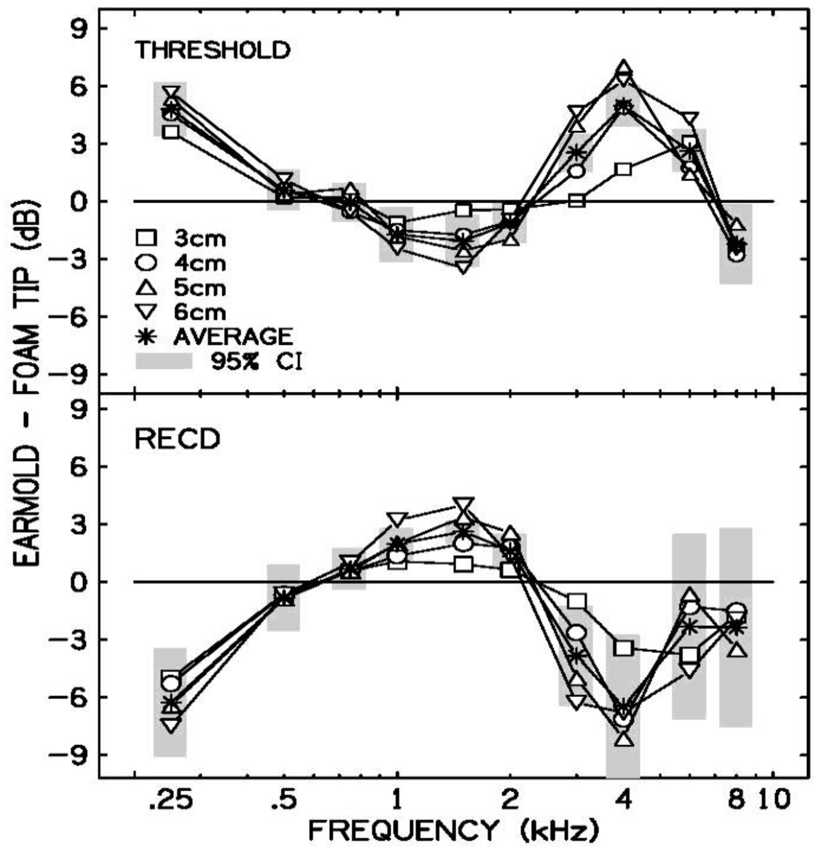

Figure 2. Average threshold (top panel) and RECD (bottom panel) changes as a function of test frequency for each length of earmold tubing relative to the thresholds and RECDs obtained with the foam tip. Positive and negative values indicate that the average threshold or RECD measured with the earmold was higher (poorer) or lower (better) than average thresholds or RECDs obtained with the foam tip, respectively. Also shown are the average threshold and RECD changes collapsed across tubing length as well as the 95% confidence interval for this collapsed data.

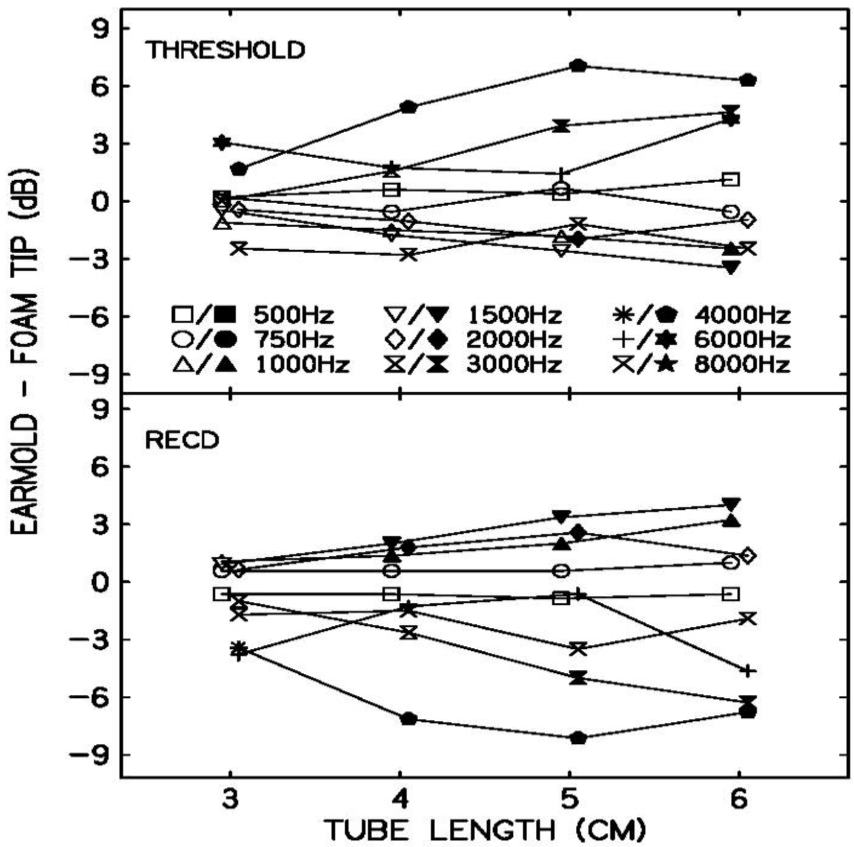

Figure 3. Average changes between earmold and foamtip as a function of tubing length for threshold measures (top panel) and RECD values (bottom panel). Filled symbols indicate a significant measured difference between earmold and foamtip.

In summary, this systematic examination demonstrates the nearly equal and opposite effects of tubing length on acoustic and behavioral measures. Specifically, as tubing length increases, sound pressure level in the ear canal decreases, hearing thresholds increase (become poorer), and the real-ear portion of the RECDs decreases, particularly at low and high frequencies. These results are consistent with a number of previous studies showing isolated examples of these effects (Munro & Buttfield, 2005; Munro & Salisbury, 2002; Scollie et al, 1998; Seewald et al, 1999).

Implications

Two implications for the hearing-aid fitting process are revealed in this demonstration. First, the same real-ear SPL can be obtained using the patient's personal earmold or using a standard foam tip. By way of example, Figure 4 shows the measured values that would occur for a patient using a foam tip (upper panel) or the patient's personal earmold (lower panel) for both the hearing thresholds and the RECD. The average data from the present study for a 3 kHz stimulus obtained with a foam tip and an earmold with a tubing length of 5 cm were used in this example. Recall that the purpose of these measures and transforms is to convert dB HL to dB SPL near the tympanic membrane. In the upper panel, adding the 19 dB REDD to the measured HL of 50 dB yields a predicted Real Ear SPL of 69 dB SPL. Likewise, the addition of the 14 dB CDD and the 5 dB RECD yields the same predicted Real Ear SPL of 69 dB SPL. The lower panel shows that the same Real-Ear SPL is predicted with the use of the patient's personal earmold. The measured HL increased to 55 dB HL due to the signal attenuation caused by the added tubing length. This attenuation also affected the REDD and RECD transforms.

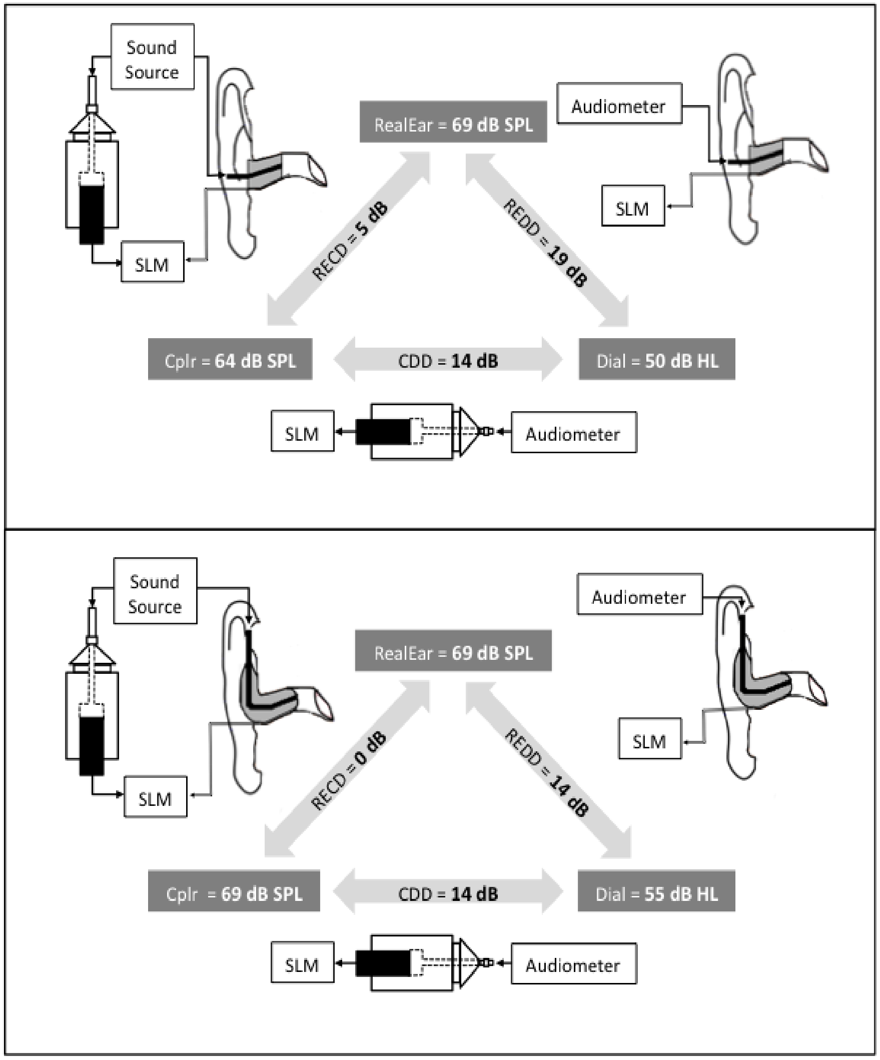

Figure 4. Real-Ear SPL levels that would occur for a patient using foam tips for both the hearing-threshold and the RECD measures (upper panel) and using the patient's personal earmold for both measures (lower panel).

Of particular benefit to the audiologist is that hearing-aid programming need not wait until the patient's earmold is received. RECDs and hearing thresholds obtained with a standard foam tip prior to the hearing aid fitting are sufficient to simulate real-ear SPL in the coupler and are equivalent to RECDs and hearing thresholds obtained with the patient's earmold. Any differences imposed by the patient's custom earmold would have a nearly equal and opposite effect on the RECD and threshold measures. Although real-ear measures are necessary to reveal the full effects of amplification (e.g., microphone arrangement, feedback management), coupler measures may be used to estimate real-ear SPL with confidence for the purpose of programming ear-level hearing aids without the patient present.

Second, significant error may be introduced into the hearing-aid fitting process with the use of inconsistent coupling methods to obtain behavioral thresholds and RECDs. Consider the effects of a foam tip used to measure hearing threshold and a personal earmold with 5 cm of tubing used to obtain the RECD as shown in Figure 5. In this example, the REDD (19 dB) added to the hearing threshold (50 dB HL) results in a Real Ear SPL of 69 dB SPL. In contrast, adding the CDD (14 dB) and RECD (0 dB) to the hearing threshold (50 dB HL) yields a predicted Real Ear SPL of 64 dB SPL; 5 dB less than the actual Real-Ear SPL. The bottom panel shows the reverse coupling condition, with a personal earmold used to obtain hearing thresholds and a foam tip to measure RECD. Although a less likely arrangement, a +5 dB error would result. Taken together, these examples demonstrate that the use of inconsistent coupling methods across hearing threshold and RECD measures may ultimately lead to inaccurate Real Ear SPL measurements, potentially causing over- or under-amplification during the hearing aid fitting process. Therefore, it is recommended that the same coupling method (custom earmold or foam tip) be used to obtain hearing thresholds and RECDs.

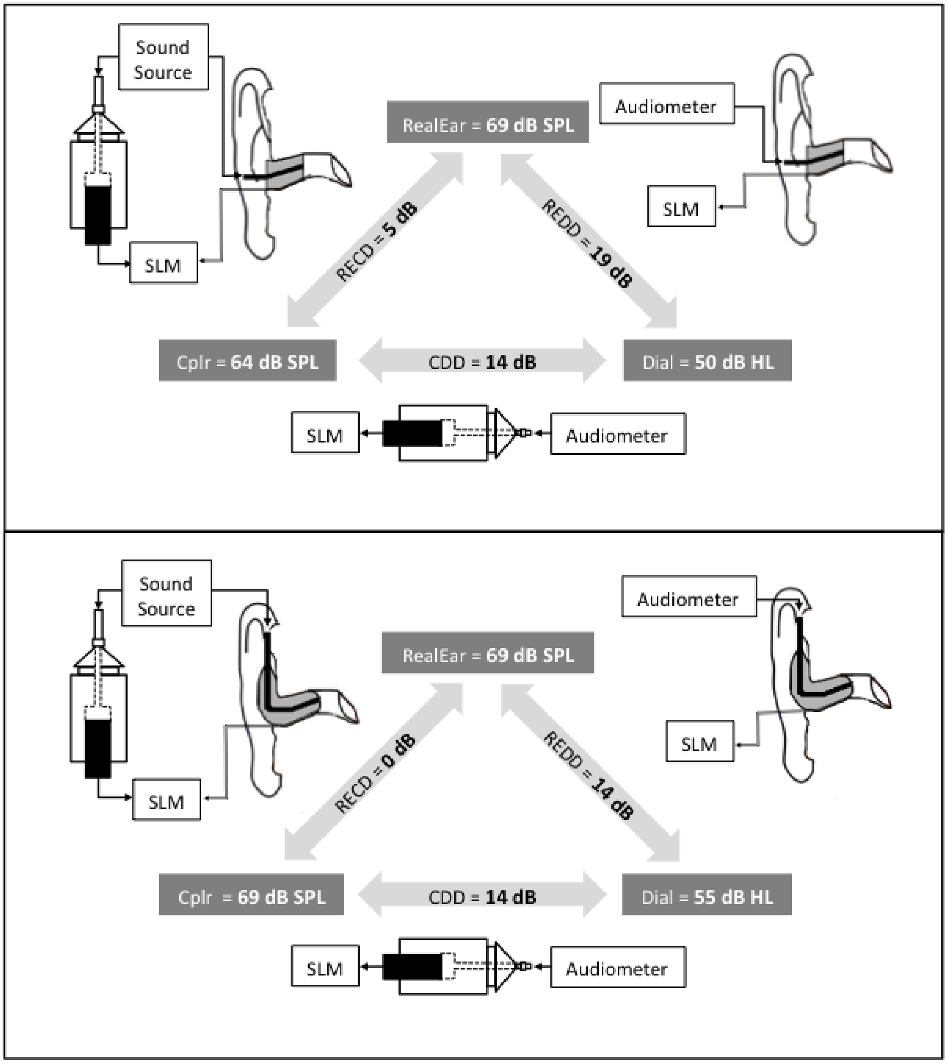

Figure 5. Real-Ear SPL levels that would occur if a foam tip is used to measure hearing threshold and a personal earmold is used to obtain the RECD (top panel). Also shown are the measured values that would occur if a personal earmold is used to measure hearing thresholds and a foam tip is used to measure the RECD (lower panel).

The audiologist may also find it expedient to simulate real-ear measures using hearing thresholds and RECDs obtained with a standard foam tip and then confirm the fitting with real-ear measures during the fitting appointment using the patient's custom earmold to capture the full effect of advanced signal processing and microphone location. Should the patient be unable to tolerate an additional set of probe-microphone measures, the fitting may also be verified using the patient's custom earmold and hearing aid coupled to an HA1 coupler. Although not ideal, the full effects of tubing length can be accounted for if careful attention is given to the placement of the earmold on the coupler.

It should be noted that certain hearing aid analyzers allow the audiologist to specify the tips that were used during threshold and RECD measurements while others do not. Also, the algorithms that govern the hearing aid analyzer may ignore certain settings or entered values if it is deemed necessary to provide the most reliable amplification targets. Thus, if the user enters contradictory information, the output is not seriously affected. When the analyzer does not allow for the specification of measurement tips or it cannot use the entered values, manufacturer-specific corrections are often used to determine amplification targets. Even for those hearing aid analyzers that allow tips to be specified, the manner in which the information is used may be difficult for the audiologist to determine from the output of the analyzer. However, given the complexity of the fitting algorithms embedded into these devices, it would be wholly impractical and time consuming for the audiologist to attempt to manage even a small portion of the calculations involved. Therefore, it is recommended that when audiologists interact with hearing aid analyzers of any kind, they use matching tips to obtain the hearing thresholds and the RECDs so as not to introduce error into these complex calculations.

Finally, although test-retest variations on the order of 5-10 dB are generally considered clinically insignificant for hearing threshold measures, this practice does not suggest that errors of the same magnitude are equally tolerable in the hearing-aid fitting process. Real-ear measures, including the acquisition of the RECD, are based on resolutions as fine as 1 dB and are highly reliable (Scollie et al, 1998; Seewald et al, 1999). The small differences in prescribed output that may arise from errors in predicting real-ear dB SPL may comprise a considerable portion of a patient's dynamic range, such as in cases of moderate to severe hearing loss. Fortunately, using the same coupling method for hearing thresholds and RECD measurements can easily reduce this problem.

It should be noted that real-ear measurements obtained in a child's ear canal are generally found to be greater than that of an adult's due to the child's ear canal being of smaller volume and shorter length. Additionally, the largely cartilaginous ear canals of newborns as well as the developmental change in absorbance in a child's ear add to the variation between adult and child measures of real-ear SPL. Therefore, a coupling mismatch between earmold and foam tip for children may also lead to variability in estimated real-ear SPL than was demonstrated with adults.

Conclusion

The purpose of this exercise was to demonstrate the effects of tubing length on RECD and hearing-threshold measures using personal earmolds as well as a standard foam tip coupled to insert earphones. Significant differences were observed as a function of tubing length across frequency, with average differences as large as 7 dB for hearing thresholds and 8 dB for RECD measures. These results indicate that inconsistent coupling methods for hearing-threshold and RECD measures may introduce significant errors into the hearing-aid fitting process. Because this error is greater for longer tubing lengths, the impact of different coupling methods between hearing-threshold and RECD measures is greater for older children and adults than for infants and young children. However, when the same coupling method (foam tip or personal earmold) is used to obtain the RECD and hearing thresholds, equal and accurate estimates of real-ear SPL are achieved. Therefore, it is recommended that the same coupling method (foam tip or personal earmold) be used to obtain both hearing thresholds and RECD measures.

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