Measuring the Real-Ear to Coupler Difference Transfer Function With an Insert Earphone and a Hearing Instrument: Are They the Same?

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Objective: **The purpose of the study was to compare the real-ear to coupler difference (RECD) measured with an insert earphone and two models of hearing instrument.**

Design: **The RECD was obtained from one ear of 18 normal-hearing subjects by subtracting the 2-cc coupler (HA1 and HA2) response from a real-ear aided response, using a conventional probe-tube microphone system. The measurements were made with a conventional ER-3A earphone and two models of behind-the-ear hearing instrument (Unitron US80, Unitron, Kitchener, Canada; and Widex Diva, Widex, Vaerloese, Denmark).**

Results: **The procedures were very reliable, with mean differences on retest of less than 1 dB. There were statistically significant differences between the mean RECDs obtained using an insert earphone compared with those obtained with each hearing instrument ($p < 0.05$). The differences were greatest when using the HA2 2-cc coupler. For example, the maximum difference in mean RECD between the insert earphone and the Widex Diva was 6 dB and 11 dB when using the HA1 and the HA2 2-cc coupler, respectively.**

Conclusions: **The RECD is dependent on the acoustic impedance of the sound source, the coupling system, and the coupler and ear. The acoustic impedance may be different for an insert earphone and a given hearing instrument. Therefore, the RECD measured with an insert earphone may not always accurately represent the difference in performance of a hearing instrument measured in the real ear and the 2-cc coupler.**

(Ear & Hearing 2005;26;27–34)

Direct measurement of real-ear hearing instrument performance can be obtained by using a probe-tube microphone system. Alternatively, real-ear performance can be derived by adding the real-ear to coupler difference (RECD) transfer function to the electroacoustic response of the hearing instrument when measured in a 2-cc coupler (Moodie, Seewald & Sinclair, 1994). Although there is no formally recognized definition for the RECD, it is generally accepted to be the difference, in decibels, between the SPL measured in the ear canal relative to the SPL measured in a coupler for the same transducer. The difference arises from the complex interaction of such factors as the impedance properties of the ear, the residual ear canal volume with an earmold in place, and acoustic leakage of amplified sound from the occluded ear canal. An RECD can also be used to convert audiometric data, measured with an insert earphone, from decibel hearing level (dB HL) to real-ear SPL. Using the RECD to derive real-ear sound pressure level (SPL) requires less cooperation from the subject; the probe tube has to be tolerated only for the duration of the real-ear part of the transfer function measurement and not for the full duration of audiometric assessment and selection/verification of the hearing instrument. A detailed description of how to use the RECD to convert both electroacoustic and audiometric data to real-ear SPL, using the RECD, is given by Munro and Lazenby (2001).

A clinical procedure for measuring the RECD has been described by Moodie et al. (1994), and most commercially available probe tube microphone systems now include an RECD protocol that uses an insert earphone and an HA2 2-cc coupler. The use of an insert earphone overcomes problems associated with changes in azimuth and movement of the reference microphone that can occur when undertaking sound field measurements in difficult-to-test populations such as young children and babies. The HA2 2-cc coupler is used in preference to an HA1 2-cc coupler because doing so reduces the possibility of low frequency leakage and accounts for the acoustical effects of the earmold plumbing.

Inherent in the derivation of real-ear SPL is the assumption that the RECD measured with one transducer (for example, an insert earphone) can be applied to a coupler measurement performed with a different transducer (for example, a hearing instrument). However, Munro and Salisbury (2002) have shown that the RECD values obtained with the procedure described by Moodie et al. (1994) is not always independent of the measurement earphone. They used two models of insert earphone to measure

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the RECD from one ear of 18 normal adult subjects. Three earmold configurations were used in the study: (1) a foam ear-tip; (2) a personal earmold with the same length of acoustic tubing as the foam ear-tip (25 mm); and (3) the same personal earmold with the appropriate length of tubing for a behind-the ear (BTE) fitting (approximately 45 mm). The results showed that there was a significant difference in RECDs measured with the two earphones. The maximum difference was 3 dB at 1.5 kHz when using the foam ear-tip and the earmold with 25 mm tubing; however, this increased to 9 dB at 1.5 kHz when the tubing was lengthened to approximately 45 mm. It is possible that differences may have been even larger if measurements had been made at intermediate frequencies. The explanation for the difference is discussed in detail by Munro and Salisbury (2002) and is thought to relate to the interaction between the acoustic impedance of the source (the earphone) and the coupling system (the ear or the 2-cc coupler). It is possible that the difference obtained with the two measurement earphones would have been smaller if an HA1 coupler had been used, since the earmold coupling would be the same for both the coupler and real-ear component and the effect of earmold tubing would cancel in the resulting RECD.

Two studies have derived accurate predictions of real-ear hearing instrument performance when using an RECD measured with an ER-3A earphone (Munro & Hatton, 2000; Seewald, Moodie, & Sinclair, 1999). This suggests that the RECD obtained with the ER-3A earphone is similar to the RECD that would have been obtained if the subject's hearing instrument had been used for the measurement. However, Munro and Hatton used a single model of hearing instrument (and Seewald et al. did not report the models used in their study). Additionally, both of these studies reported data at a limited number of frequencies (Munro & Hatton, 10 frequencies; Seewald et al., five frequencies). It is possible that differences may have occurred with different models of hearing instrument or/and at intermediate frequencies. No study has systematically compared the mean RECD measured with the ER-3A earphone and a hearing instrument.

The aim of the present study was to measure the RECD obtained with examples of hearing instruments and to compare these to the conventional ER-3A earphone RECD. This extends previous studies in three ways: (1) the insert earphone RECD was compared directly with the RECD measured with hearing instruments; (2) data were collected in both the HA1 and HA2 2-cc coupler to determine if the differences are smaller when using the HA1 coupler; and (3) data were collected at 1/12 octave intervals from 0.2 to 6 kHz to determine the extent of any differences at intermediate frequencies nor previously reported.

METHODS

Subjects

Eighteen subjects (6 men, 12 women) with normal hearing, having a mean age of 35 yr (range, 22–55 yr), were recruited to the study. A minimum of 16 subjects was required for the study to have a statistical power in excess of 80% (to show a mean difference in paired data of 3 dB [SD = 4]) at a two-tailed significance level of 0.05, using the Student *t*-test). Subjects were required to demonstrate normal middle ear function on tympanometry (middle ear pressure + 50 to −50 daPa, middle ear compliance + 0.3 to + 1.5 ml with a probe tone frequency of 226 Hz). All subjects had a personal unvented acrylic shell earmold; the internal diameter of the acoustic tubing was 2 mm, and the tubing length was held constant at 45 mm across all subjects. Measurements were made from one ear of each subject: Equal numbers of right and left ears were tested.

Procedures

All measurements were made in a sound-treated room. The acoustic signal was delivered to the ear and coupler using the ER-3A when measuring an insert earphone RECD and via a sound field loudspeaker when measuring a hearing instrument RECD. All real-ear measurements were made using the personal earmolds and with the probe tube inserted to a constant depth from the intertragal notch of 31 mm for male subjects and 28 mm for female subjects (Moodie et al., 1994). This insertion depth means that it is likely that the probe tube is within 5 to 6 mm of the tympanic membrane, since the length of the average adult ear canal is 24 to 25 mm (Zemplenyi, Gilman & Dirks, 1985) and the typical distance from the ear canal opening to the tragus is 10 mm. The important point is that the probe tube was in the same position for all measurements.

The Audioscan RM500 real-ear system was used for all measurements. The calibration of the coupler microphone and the probe module was checked at the beginning and at various intervals throughout the study, following the instructions supplied in the user guide. The coupler microphone was calibrated at the start of each test session. A new probe tube was used for each subject and this was calibrated before use. The order of RECD conditions was balanced across subjects. Each real-ear response was

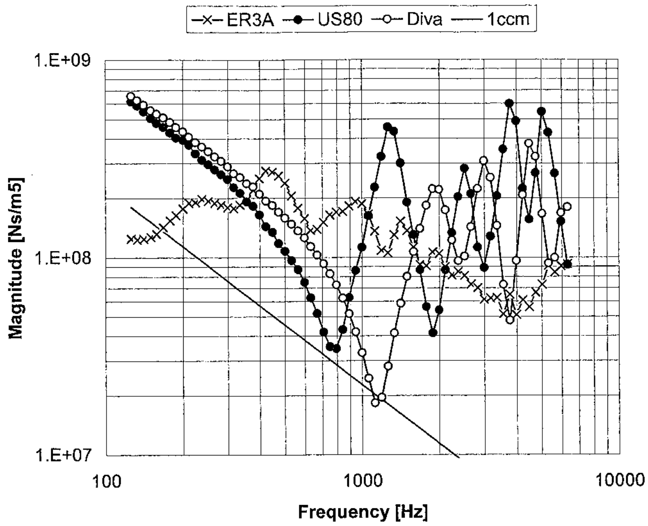

Fig. 1. Acoustic impedance of the Unitron US80, Widex Diva, and ER3 earphone compared with a 1 cc cavity.

measured twice (with the probe tube and earmold being completely removed and reinserted between measurements) to investigate test-retest reliability.

Two hearing instruments were selected on the basis of different acoustic impedance values. The equipment used to measure the acoustic impedance of the hearing instruments was developed by Phonak AG (Stirnemann, Reference Note 2). This equipment consists of a conventional hearing instrument receiver and microphone in combination with a standard PC sound card. It works in real time, using MATLAB technical programming software. The two BTE hearing instruments used in the study were the Unitron US80 and the Widex Diva. These hearing instruments were used with the ear hook as supplied by the U.K. distributor (the details of which were not recorded). Figure 1 shows the acoustic impedance of these hearing instruments and the ER-3A earphone compared with a cavity of 1 cc (typical of an occluded human ear canal). Between 1 and 2 kHz, the acoustic impedance of the two hearing instruments differ by more than a factor of 10. The impedance of the 1 cc cavity is matched by the Unitron US80 at 0.8 kHz, whereas it is not matched by the Widex Diva until 1.1 kHz. On the other hand, the acoustic impedance of the ER-3A earphone is higher and somewhat smoother than the two hearing instruments.* For this reason, the RECD measurement is less sensitive to the impedance of the ER3 earphone.

The Unitron US80 is a medium- to high-power, linear hearing instrument. It was set to give approximately 20 dB gain at mid-frequencies in the HA2 2-cc coupler. The gain control was fixed with tape for the duration of the study. The Widex Diva is a nonlinear digital hearing instrument. It was also set to give approximately 20 dB gain at mid-frequencies in the HA2 2-cc coupler (the gain was reduced for low input levels and increased for high input levels to give a linear response). Feedback cancelling, adaptive directional microphone beam forming, and noise reduction were disabled for the duration of the study.

*The acoustic impedance of the ER3 earphone decreases at low frequencies due to a poor acoustic seal.

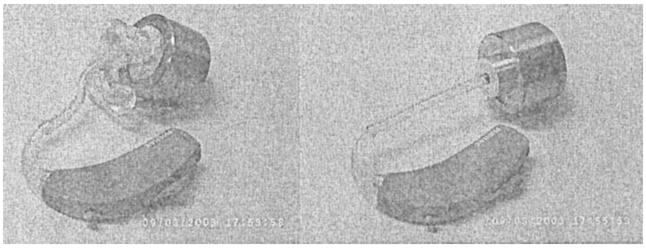

Fig. 2. Normal configuration of the HA1 2-cc coupler with a behind-the-ear hearing instrument is shown in the left panel. Adaptor used in the present study is shown in the right panel. Dimensions of the acoustic tubing used with the adaptor were identical to that used in the personal earmolds.

Insert Earphone RECD

The insert earphone was attached to the Audioscan RM500 via the auxiliary loudspeaker socket, using a 3.5-mm male stereo jack to ¼-inch female stereo jack adaptor. A pure-tone swept signal was measured in the 2-cc coupler and then in the subjects' ear canal.† When making the coupler measurement, the nipple of the insert earphone was attached to the tube of the HA2 coupler. When using the HA1 coupler, the nipple of the earphone tube was attached to 45 mm of earmold tubing. This was the same length of tubing that was used in all of the personal earmolds. The tip of the tubing was held flush to the entrance of the coupler by inserting it into a small metal ring that had been specially made for the study (see Fig. 2). This was used in preference to the personal earmolds, since it should reduce the risk of low frequency leaks that can occur when attaching an earmold to the HA1 coupler. Since the tubing length was identical to that used in the earmolds, the coupler measurements should be equivalent. The data were extracted from the Audioscan RM500, using Audioscan Xdata-32 software at 1/12 octave intervals from 0.2 to 6 kHz. The RECD was then calculated by subtracting the coupler val-

†We did not use the standard RECD protocol on the Audioscan RM500 because we wanted to investigate the validity of the RECD concept and not a particular manufacturers RECD protocol.

TABLE 1. Mean test-retest difference, in decibels, for the real-ear responses obtained with each transducer

	250 Hz	500 Hz	750 Hz	1000 Hz	1500 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz
Insert	−0.3 (1.3)	−0.2 (1.2)	0.0 (0.8)	0.1 (0.7)	0.0 (0.6)	0.1 (0.6)	0.4 (1.8)	0.2 (2.4)	−0.4 (4.3)
US80	0.6 (1.5)	0.6 (0.2)	0.4 (0.4)	−0.1 (0.5)	0.0 (0.6)	0.1 (0.5)	0.0 (0.6)	−0.1 (1.0)	0.0 (0.8)
Diva	0.2 (3.1)	0.2 (0.7)	0.0 (0.6)	0.0 (0.8)	0.0 (0.8)	0.1 (0.6)	0.0 (0.7)	−0.2 (1.2)	0.3 (2.4)

One standard deviation of the difference is given in parentheses (n = 18).

ues from the mean of the two real ear values obtained from each subject.

Hearing Instrument RECD

The procedure for measuring the RECD with each of the hearing instruments involved measuring a normal real-ear aided response (REAR) and a 2-cc coupler response with an input of 55 dB SPL (background noise was always less than 40 dB SPL). The tubing length was held constant to remove this as a confounding variable. A length of 45 mm was used because this is typical for an adult BTE fitting. It was important that the reference microphone was placed close to the hearing instrument microphone for the real ear measurement since Feigin et al. (1990) have shown substantial differences between the level measured at the hearing instrument microphone and the reference microphone location. To do this, the reference microphone was removed from the probe module: This enabled it to be positioned directly on top of the hearing instrument adjacent to the microphone inlet port.

Statistical Analysis

The data were normally distributed and have been summarized using mean values and standard deviations. The difference on retest and the difference between the mean RECDs measured with the different transducers were analyzed statistically by using repeated-measures analysis of variance (ANOVA). All 60 frequencies, over the range 0.2 to 6 kHz, were used in the analysis. The degrees of freedom were modified using the Greenhouse-Geisser correction when there was a statistically significant deviation from sphericity on the Mauchly test (Kinnear & Gray, 1999).

RESULTS

Test-Retest Data

The mean test-retest differences for the real-ear SPL are summarized in Table 1 for the main audiometric frequencies. The mean difference was close to 0 dB, with a standard deviation less than 1 dB. The test-retest difference was analyzed by using a two-factor, repeated-measures ANOVA (frequency [60], test [2]). The difference on retest was not statistically significant (ER-3A earphone, $F[1,17] = 0.01$: $p = 0.94$; Unitron US80, $F[1,17] = 1.7$: $p = 0.21$; Widex Diva, $F[1,17] = 2.9$; $p = 0.11$). There was also no statistically significant interaction with frequency for the ER-3A earphone ($F[59,1003] = 0.61$: $p = 0.99$) but there was a significant interaction for the Unitron US80 ($F[59,1003 = 2.9$: $p < 0.01$) and the Widex Diva ($F[59,1003] = 2.7$: $p < .01$). Since the differences were small, an average of the two values was used to obtain a more accurate measure of real-ear SPL for reach subject.

RECD Transfer Functions

The RECD transfer function was derived by subtracting the HA1 and HA2 coupler responses from the average of the two real-ear measurements. These component parts of the RECD are shown in Figure 3 for the insert earphone (top panel), Unitron US80 (middle panel), and Widex Diva (bottom panel). Each panel shows two expected features: (1) the SPL of the real-ear response is higher than both 2-cc coupler responses, and (2) the SPL is higher in the HA2 than the HA1 2-cc coupler at the highest test frequencies.

The mean RECD transfer functions obtained with all three transducers are shown in Figure 4 when using the HA1 (top panel) and HA2 2-cc (bottom panel) 2-cc coupler. A positive value indicates the extent to which the SPL measured in the real ear exceeds the SPL measured in the 2-cc coupler. Although the mean RECDs were similar for the three transducers, they are not the same: differences occurred in the mid-frequencies and were greatest when the RECD was measured using the HA2 2-cc coupler. The largest differences occurred between the Widex Diva and the insert earphone: 6 dB and 11 dB, in the HA1 and HA2 2-cc coupler, respectively. The corresponding values for the Unitron US80 and the insert earphone were 4 dB and 6 dB, respectively.

The mean RECD data for each coupler were analyzed by using a separate two-factor, repeated-measures ANOVA (frequency [60], transducer [3]). There was a statistically significant difference in mean RECD between transducers (RECD/HA1, $F[2,34] = 6.6$: $p < 0.01$; RECD/HA2, $F[2,34] = 7.1$: p

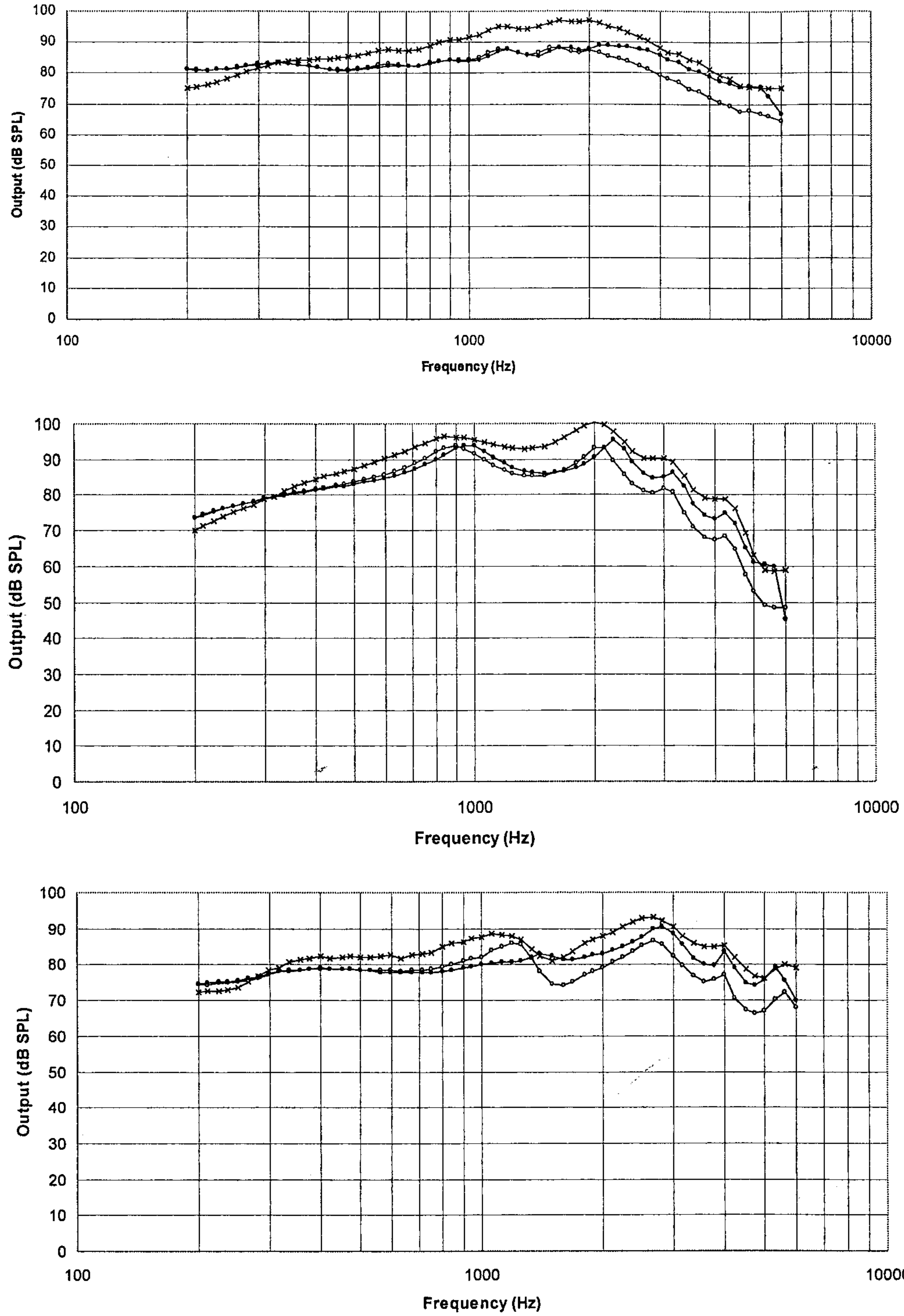

Fig. 3. Mean data measured with ER-3A (top panel), Unitron US80 (middle panel), and Widex Diva (bottom panel). Each panel shows real-ear (crosses), HA1 (open circles), and HA2 (filled) output, in SPL, as a function of frequency.

< 0.01). This finding means that there was a difference between transducers when the data were collapsed across frequencies. There was also a statistically significant interaction with frequency (RECD-HA1, $F[118,20061] = 14.7$: $p < 0.01$; RECD-HA2, $F[118,2006] = 42.6$: $p < 0.01$). This indicates that the transducers behaved differently from each other at some frequencies.

The mean RECDs obtained with each transducer were then compared with each other. This analysis resulted in three ANOVAS per coupler: (1) insert earphone and Unitron US80, (2) insert earphone

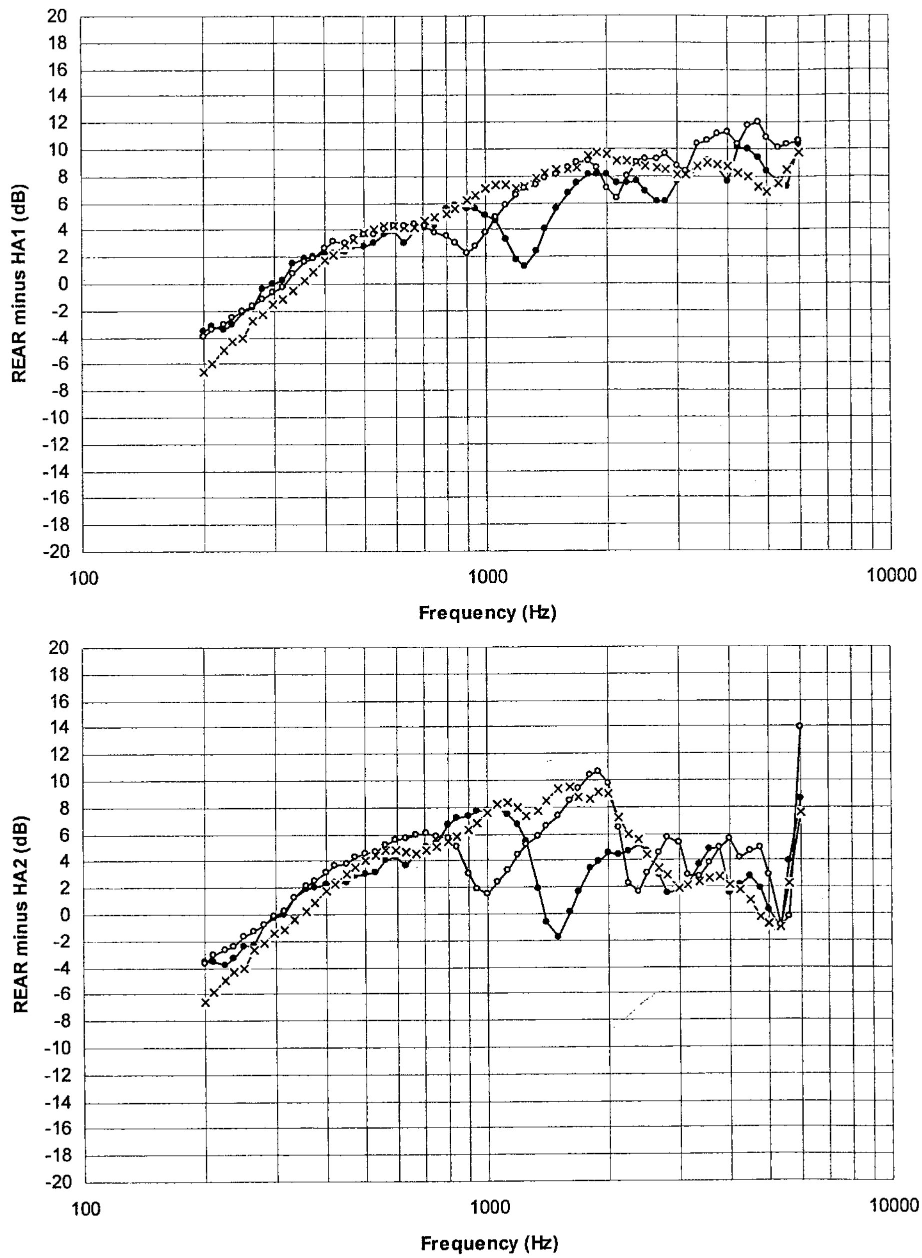

Fig. 4. Mean real-ear to coupler difference transfer function, as a function of frequency, measured with the HA1 (top panel) and HA2 (bottom panel). Each panel shows data for the ER-3A (crosses), Unitron US80 (open circles), and Widex Diva (filled circles).

and Widex Diva, and (3) Unitron US80 and Widex Diva. A Bonferroni correction for multiple comparisons changed the 5% significance level from 0.05 to 0.015. All combinations were statistically significant except when the Unitron US80 was compared with the insert earphone in the HA1 2-cc coupler. There was a statistically significant interaction with frequency for every combination of transducer.

DISCUSSION

The test-retest differences for the real-ear measurements were small and consistent with those reported previously in the literature (e.g., Munro & Davis, 2003).

There is good agreement between the mean ER-3A earphone RECDs measured in the present study and those reported by Munro and Davis (2003) and Munro and Hatton (2000). The mean RECDs measured with the hearing instruments are different from those obtained with the insert earphone; in addition, these differ from the mean hearing instrument RECD reported by Munro and Hatton (2000). The findings are also consistent with Munro and Toal (Reference Note 1), who showed that there was a mean difference in RECD of 4 dB at 2 kHz when measured with an insert earphone and a hearing instrument. This confirms that the RECD is not independent of the measurement transducer. The results also demonstrate that it is not possible to use a standard correction factor to convert from an RECD measured in an HA2 coupler and an HA1 coupler; for example, a correction of + 0.9, −2.2, and + 2.7 dB is required at 1 kHz for the ER-3A, Unitron US80, and Widex Diva, respectively.

The SPL developed in a coupler or an ear canal is dependent on the impedance of the coupler or ear canal, the impedance of the coupling system, and the impedance of the sound source (Egolf, Feth, Copper & Franks, 1985; Gilman, Dirks & Stern, 1981; Sanborn, 1998). Since the RECD is the difference in SPL developed in the ear canal and the SPL developed in the coupler, it will also be dependent on these factors. If the impedance of the coupling system and the source are grouped together as Zs and the impedance of the ear and coupler are taken as Ze and Zc, respectively, then

$$\text{RECD} = (Ze/Zc)*(Zs + Zc)/(Zs + Ze) \qquad (1)$$

If Zs is much greater than either Ze or Zc, this simplifies to

$$\text{RECD} = Ze/Zc \qquad (2)$$

However, Sanborn has shown that for the ER-3A earphone and several hearing instruments (all coupled to the ear with earmolds), the combined transducer and earmold coupling has an impedance value that is comparable to the impedance of the ear and coupler. Therefore, equation 1 applies, and RECD may be expected to be dependent on the impedance of the sound source and the impedance of the coupling system.

The difference between the mean RECDs in the present study are smallest when using the HA1 2-cc coupler. This is because the transmission path (i.e., earmold coupling) is the same when measuring the real-ear and the HA1 coupler response. Thus, the differences when using the HA2 coupler are due to the impedance of the hearing instruments and different earmold couplings and ear canals: the differences when using the HA1 coupler are due to the impedance of the hearing instruments in combination with the same earmold coupling and different ear canals.

Despite the difference in mean RECDs reported in the present study, Seewald et al. (1999) and Munro and Hatton (2000) have shown that the derived real-ear performance of a hearing instrument, obtained using an ER-3A earphone RECD, is a clinically acceptable procedure. Munro and Hatton reported a mean difference of 2 dB at 1.5 kHz between the measured and derived real-ear SPL, and a similar magnitude of error was reported by Seewald et al. (1999). It is possible that larger differences did occur but at frequencies that were not reported. For example, Seewald et al. did not report data at frequencies between 1 and 2 kHz, where differences might have been expected to occur. On the other hand, Munro and Salisbury (2002) have shown that the difference reduces as the tubing length decreases. Seewald et al. used subjects under 12 yr of age (three were preschool age) and it is likely that the earmold tubing was shorter than the 45 mm used in the present study. However, the fact remains that the tubing length is removed from the equation altogether when using the HA1 coupler and differences still remain.

The RECD also depends on the acoustic impedance of the actual hearing instrument and this will be influenced by the use of acoustic damping. Although filter details were not recorded in the present study, the coupler responses (shown in the middle and bottom panels of Fig. 3) are not atypical of those obtained in the general clinic population. However, it is not yet clear if the findings will generalize to other BTE instruments, across different acoustic damping conditions and for different lengths of tubing. For some combinations of hearing instrument, earmold tubing and damping, the difference may be small and not clinically significant.

If the differences are shown to be clinically significant, then there are a number of measures that can be taken. First, the RECD can be measured in an HA1 coupler. This will reduce but not necessarily eliminate the error. Hearing instrument performance would also need to be measured in an HA1 coupler to derive real-ear performance and this may introduce errors due to low frequency leakage when attaching the earmold to the coupler. Second, it may be appropriate to measure the RECD with the subject's hearing instrument instead of with an insert earphone.‡ Again, this is not without difficulty, since sound field measurements are influenced by the location of the probe tube reference microphone in addition to movement of the subject during the measurement (as this may affect the ability of the probe-tube reference microphone to control the sound pressure level). The ability to position the reference microphone directly beside the hearing instrument microphone, as used in the present study, is not available in clinical practice. However,

‡When selecting the most appropriate hearing instrument from a range of devices, it may be necessary to measure an RECD from each individual hearing instrument. An alternative would be to apply a correction factor to make the RECD measured with one hearing instrument equal to the RECD measured with a different hearing instrument but this correction factor will be transducer-specific.

sound field measurements can be avoided altogether with direct audio input, or, if the signal is delivered direct to the hearing instrument receiver from the manufacturers fitting software: this latter approach is already used by some manufacturers (for example, Phonak AG use this approach with their RECD-Direct protocol). The repeatability of the RECD measured with the latter approach is likely to be similar to that reported for earphone RECDs (e.g., Sinclair, Beauchaine, Moodie, Feigin, Seewald, & Stelmachowicz, 1996). This would be preferable to making sound field RECD measurements or relying on average RECD values, which are known to vary considerably across individuals (Bagatto, Scollie, Seewald, Moodie, & Hoover, 2002).

We are currently undertaking a study that compares the measured and derived real-ear response for a wide range of hearing instruments to determine the magnitude of error that may be present. We are also deriving real-ear hearing instrument performance using both HA1 and HA2 2-cc coupler protocols. In the meantime, we continue to measure the RECD with an insert earphone and an HA2 coupler because errors appear to be restricted to a limited frequency range and, at least for some models of hearing instrument, are no more than 5 dB.

CONCLUSIONS

It is standard clinical practice to derive the real-ear–aided response by adding an RECD obtained with an insert earphone to the coupler response of a hearing instrument. However, the present study has shown that there are occasions when the RECD obtained with an insert earphone differs from that obtained with a hearing instrument. A possible solution would be to modify the RECD protocol to use the HA1 2-cc coupler and to use the hearing instrument as the sound source. However, these modifications are not trivial, and further work is required to establish if the errors reported in the present study are unacceptable for clinical practice.

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