Update on RECD Measures in Children

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Introduction

The amplification requirements for an individual are normally based on data obtained during audiometric assessment. The precise inter-relationship between the frequency-specific amplification characteristics and the assessment data is most readily appreciated when they have been measured at the same reference point (and in the same units). This is important if the audibility of speech and the closeness of fit between uncomfortable loudness level (ULL) and maximum power output (MPO) are to be determined. Using the ear canal as the reference point has the additional advantage of accounting for differences in external ear acoustics across subjects. A probe-tube microphone can be used to measure real-ear sound pressure level (SPL) directly; however, in some populations (such as infants and children) the probe tube may not be tolerated for extended periods of time. An alternative is to derive (sometimes called ‘predict’) the real-ear SPL by adding an individually measured acoustic transfer function to both the audiometric and electroacoustic data. The acoustic transfer function in question is known as the ‘real-ear-to-coupler difference’ (RECD).

It is more than 15 years since Feigin, Kopun, Stelmachowicz and Gorga (1989) demonstrated that the infant RECD varies significantly from the adult and it is more than 10 years since Moodie, Seewald and Sinclair (1994) described a simple clinical procedure for measuring the RECD. However, implementation into clinical practice has been somewhat slow. In a survey of current practice in ‘good pediatric services’, the percentage routinely performing RECD measurements was 20% and 40% in the UK and USA respectively (Bamford et al. 2002). The purpose of this chapter is to update the clinician on recent RECD publications. The aim is to encourage the clinician to measure and integrate RECDs into the hearing instrument fitting process. The chapter extends the recent Phonak Focus article on RECDs (Munro 2004) by expanding the review of published articles and providing information about the most recent studies from our laboratory that have not yet been published (and where the clinical implications for the pediatric population have still to be determined).

What is an RECD Acoustic Transfer Function and What Does It Look Like?

Real ear measurement procedures such as real-ear unaided response, real-ear aided response, real-ear occluded response and real-ear insertion gain are defined in an International Standard (ISO 12124, 2001). Absent from ISO 12124 is a definition for the RECD acoustic transfer function; however, this is generally accepted to be the difference between the SPL measured in the occluded ear canal relative to the 2cc coupler. The clinical protocol for measuring the RECD uses an insert earphone to deliver the signal and compares the SPL generated in the real ear with the SPL generated in the HA2 2cc coupler. The difference, in decibels, between the two measurements is the RECD.

If life were straightforward then the SPL measured in the occluded ear canal and 2cc coupler would...
be the same: the RECD would be zero at all frequencies. However, this is not the case. There are differences between the occluded ear canal and the 2cc coupler due to a combination of factors including the impedance properties of the ear, the volume of the occluded ear canal, and the acoustic leakage of amplified sound from the occluded ear canal. As a result, the SPL generated in the occluded ear canal is usually higher than in the 2cc coupler. As an example, the SPL generated in an occluded ear canal, and in the HA1 and HA2 2cc coupler is shown in figure 1. In this case, the adult ear canal was occluded using an unvented personal (sometimes called ‘customized’) earmold with approximately 45 mm of acoustic tubing. The signal was delivered via an ER3 insert earphone. The figure shows that the SPL in the ear canal is higher than in the coupler, for the reasons given above. In addition, the SPL measured in the couplers differ at the higher frequencies: the SPL is lower in the HA1 than the HA2 coupler because it includes the influence of the sound bore of the earmold.

The RECDs obtained for this individual are shown in figure 2. A positive value indicates the extent to which the SPL is higher in the occluded ear canal compared to the coupler. The magnitude of the RECD is greatest at higher frequencies because the acoustic impedance of the 2cc coupler decreases more than that of the occluded ear canal; this results in a greater difference in SPL between the two cavities. The effect of the earmold sound bore is eliminated from the RECD when the SPL is measured in the HA1 coupler. This occurs because the earmold plumbing is part of the transmission path when measuring the SPL generated in both the ear and the HA1 coupler: the effect of the sound bore is eliminated when these are subtracted to generate the RECD. The influence of the sound bore is present when the RECD is measured with an HA2 coupler since this is part of the transmission path when measuring the SPL in the ear canal but not the coupler. It may be more appropriate to refer to the latter as an earmold and-real-ear-to-coupler difference (E-RECD). The latter will include the effect of amplified low frequency sound escaping via the vent but it does not include the effect of sound directly entering the ear.

1 Unlike the HA1, the HA2 includes an earmold simulator so does not require the earmold to be connected using putty.
Integrating the RECD into the Fitting Process

With co-operative subjects, it is generally possible to use a probe-tube microphone system to measure ear canal SPL directly. When this is done for audiometry it is known as ‘in-situ audiometry’: when it is done for hearing instrument performance it is known as real-ear measurement (for example, real-ear aided response [REAR] and real-ear saturation response [RESR]). However, there are occasions when these clinical procedures are not tolerated by the subject, especially the infant and young child. In these subjects, in particular, it may be appropriate to derive ear canal SPL using the RECD in conjunction with traditional clinical procedures.

The RECD can be integrated into several stages of the hearing instrument fitting process as shown in figure 3. The first stage involves audiometric assessment when data have been collected using an insert earphone. The hearing threshold, in decibels hearing level (dB HL), is converted to ear canal SPL in a two-step process. In Step One, the assessment data are transformed from dB HL to dB SPL. The transformation factor is known as the ‘coupler-to-dial difference’ (CDD) and is similar to the frequency-specific reference equivalent threshold SPLs (RETSPL) used in the physical calibration of the pure tone audiometer. The CDD and RETSPL values are not identical because the measurements require different coupler configurations.\(^2\) This step occurs in the fitting software and does not require the clinician to make any measurements or calculations. Once the data have been transformed to dB SPL in the coupler, Step Two involves transferring the data from the 2cc coupler to the ear canal. This is achieved by measuring and adding the RECD. This two-step process is illustrated in figure 4. These calculations are usually performed automatically in the fitting software after the clinician has entered the assessment data and the RECD.

\(^2\) The RETSPL values apply when the sound tube nipple of the earphone is fixed flush to the acoustic coupler (ISO 389–2, 1994) not via the 25 mm of flexible tubing used when measuring the electroacoustic performance of a behind-the-ear hearing instrument (IEC 60126, 1973).
Figure 3. The ear canal SPL can be derived for audiometric and electroacoustic data using the RECD.

There is an alternative method that combines this two-step process and involves adding the real-ear-to-dial difference (REDD) to the assessment data (Munro and Lazenby 2001). This alternative method is useful when the supra-aural earphone is used for audiometric assessment since the RECD requires access to a 6cc coupler (IEC 60318–3) and this is generally not available in clinical practice. However, this method is equally valid for the insert earphone.

The second stage of the fitting process where the RECD is useful is when hearing instrument performance has been measured in a 2cc coupler. Once again, the reference point can be transferred from the 2cc coupler to the ear canal using the RECD. This is illustrated in figure 5. Unless the hearing instrument is saturated, the microphone location effects (MLEs) have also to be added: these are of the order of a few decibels and average default values are used by the fitting software.

The RECD is required for both the selection and the verification of hearing instrument performance. The clinician uses the selection process to provide a hearing instrument with amplification characteristics that closely match target values. The verifica-

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**Figure 4.** Audiometric data (obtained with insert earphones) are converted from dB HL to dB SPL by adding the CDD transform. These are then transferred from the coupler to the real ear using the RECD transfer function. Hypothetical numbers have been used to illustrate this two stage process.

**Figure 5.** Electroacoustic data are transferred from the coupler to the real ear using the RECD transfer function. Hypothetical numbers have been inserted for illustration.
The selection process is used to confirm that there is a close match to target when the hearing instrument is worn by the subject. This means that selection and verification of amplification characteristics can take place in the ‘simulated real ear’ as illustrated in figure 6. The same model of 2cc coupler should be used when measuring hearing instrument performance and RECD.

Despite the similarity between the selection and verification process shown in figure 6, there are two important differences. Firstly, the selection of electroacoustic characteristics is under the control of the clinician. Secondly, at this stage, an individually measured RECD with the subject’s personal earmold may not be available; therefore, age-appropriate average values are used in the fitting software. Verification is required to ensure that the instrument is delivering the appropriate SPL to the ear canal. The electroacoustic characteristics are measured at the normal user settings and require the individually-measured RECD obtained with the personal earmold.

The RECD obtained from an individual will differ depending on the earmold used to occlude the ear canal. The RECDs obtained using two different earmold configurations are shown in figure 7. The adult ear canal was occluded using a disposable foam ear-tip (open circles) and a personal earmold (filled circles). The difference between the two RECDs is due to differences in acoustic leakage, depth of earmold insertion and length of sound bore high frequencies. Clinicians interested in the influence of earmold insertion depth on the RECD will find the work by Seewald, Cornelisse, Richert and Block (1997) on CIC instruments informative.

In order to use the same RECD to derive real-ear SPL for audiometric and electroacoustic data, it is necessary to use the same earmold; otherwise, two RECD measurements per ear will be required (or, alternatively, an REDD as well as an RECD). Clinical observation suggests that infants are often prepared to tolerate insert earphones for audiometric assessment if these are coupled to the ear using their personal earmold. This means that only one RECD (with personal earmold) per ear is required from the subject when deriving real ear SPL of both audiometric and electroacoustic data. A detailed description of how to use the RECD to convert audiometric and electroacoustic data into real ear SPL is given by Revit (1997), Munro and Lazenby (2001) and Scollie and Seewald (2002).
Why Is It Helpful to Use the Ear Canal as the Reference Point?

There are at least two reasons why it is helpful to convert all variables to ear canal SPL. The first reason is related to the inter-relationship between variables, and the second to variations in ear canal dimensions and acoustics between individuals.

1. The Inter-Relationship Among Variables

The precise inter-relationship between assessment data and the amplification characteristics can only be readily appreciated when these are measured at the same reference point. This point was recognized many years ago (for example, DeVos 1968; Gengel, Pascoe and Shore 1971; Erber 1973; Byrne 1978) and it is one of the key building blocks of the Desired Sensation Level fitting method for children (Seewald 1995). The data can then be displayed on a single graph referred to as an ‘SPLogram’ as shown in figure 8. It is clear from this figure that average conversational speech is not audible to this subject without amplification. Amplified speech is audible and located in the middle of the subject’s dynamic range. Also, the maximum output of the hearing instrument has been set close to the subject’s uncomfortable loudness level. Similar approaches can now be implemented in other prescription fitting procedures including the National Acoustic Laboratory NL1 fitting software where it is called a ‘speech-o-gram’ (Dillon 1999). Traditionally, most clinicians have used real ear insertion gain (REIG) measures and these can be calculated from the data presented in figure 8 by subtracting the aided speech spectra from the unaided speech spectra. However, this is less informative since it is not easy to visualise if speech is above threshold (and it involves the measurement of two real ear responses) nor does it provide information about the match between ULL and MPO.

2. Variations in Ear Canal Dimensions

The second reason for using the real ear as the reference point is that it eliminates variations across individuals due to differences in ear canal dimensions. The implications of different ear canal dimensions and acoustics on audiometric data have been
Figure 8. The SPLogram for one ear of a hypothetical subject with a hearing impairment. Normal threshold of hearing is shown by the thin pecked line. The dynamic range of the subject is the area between the hearing threshold (filled circles) and the uncomfort- able loudness level (open circles). Unamplified speech (S) is inaudible to the subject. Amplified speech (A) is audible since it is located approximately mid-way within the subject’s dynamic range. The maximum output of the hearing instrument (M) has been set so that it is approximately the same level as the uncomfortable loudness level.

reported by Seewald and Scollie (1999), Ching and Dillon (2003), and Marcoux and Hansen (2003). Audiometric transducers such as the supra-aural and the insert earphone are based on calibration data which aim to give 0 dB HL in a normal hearing adult. However, this is not the case in the infant or child who has a smaller external ear canal than the ‘average’ adult. The SPL generated by an insert earphone in the infant ear canal will be higher than the SPL generated in the adult ear canal for a given dial reading (Seewald and Scollie 1999). Consequently, the severity of the hearing loss will appear less than in the adult. However, as the child grows, the ear canal volume will increase and the audiometer dial reading will need to be increased in order to reach the same SPL at the eardrum. Consequently the child will appear to have a progressive hearing loss. This means that the audiometer dial reading does not accurately reflect the hearing thresholds in subjects who do not have adult-like ear canal dimensions. The high inter-subject variability in the acoustic properties of the external ear is not restricted to infants and young children. For example, Saunders and Morgan (2003) reported that the distribution of eardrum SPL for a fixed dial level at 1 kHz was 40 dB in a group of 1814 adults. This demonstrates that it is inaccurate to assume that, across ears, a given HL signal will result in the same ear-canal SPL. This problem can be eliminated if the reference point for measuring SPL is the ear canal since the threshold of hearing will be the same regardless of the audiometric transducer and the external ear acoustics. In a case study of an 8-month old hearing-impaired infant, Moodie, Sinclair, Fisk and Seewald (2000) showed that the hearing threshold increased by as much as 18 dB when the child’s RECD was used instead of average adult values when deriving ear canal SPL.

Some authors (for example, Ching and Dillon 2003; Marcoux and Hansen 2003) have argued that it is preferable to use a standard pure tone audiogram (corrected for the difference between adult and infant ear canal acoustics) instead of the SPLogram since this format is familiar to clinicians and allows a direct comparison between audiometric data of a child and that of a normally hearing adult. This is easily performed in the fitting software and is referred to as...
‘predicted HL’ values (HLp) by Seewald, Ramji, Sinclair, Moodie and Jamieson (1993), and ‘equivalent adult hearing level’ (HLae) by Dillon (2001). It involves correcting the HL data for the difference between the infant and adult RECD (see figure 9). In practice, some clinicians use both approaches: the corrected pure tone audiogram is used when comparing subjects against the normal 0 dB HL line but the SPLogram is used when selecting and verifying amplification characteristics.

Variations in ear canal dimensions also have implications when using a hearing instrument. The smaller volume of the infant ear canal means that the amplified signal will have a higher SPL than in the adult ear canal. Therefore, it is necessary to measure or derive hearing instrument performance in the infant’s ear canal.

**Does Middle Ear Pathology Affect Ear Canal SPL?**

A ventilation tube or perforation of the eardrum will increase the effective volume of the ear canal and this will result in a reduction in acoustic impedance. The output of an audiometer or hearing instrument will need to be increased for the ear canal SPL to be equivalent to the level generated in the ear when no ventilation tube (or perforation) is present. There will be a corresponding reduction in the RECD since the real-ear component of the RECD will also have reduced.

A series of studies have confirmed the effect of middle ear pathology on the RECD (Martin, Munro and Lam 2001; Martin, Munro and Langer 1997; Martin, Westwood and Bamford 1996). Martin et al. (1996) measured the RECD in two groups of 16 children aged between four and seven years. One group had a functioning ventilation tube as confirmed by otoscopy and large ear canal volume on tympanometry: there was no evidence of middle ear pathology in the control group. The mean difference in RECDs between the two groups was 15 dB over the frequency range 125 to 750 Hz. In a further study, Martin et al. (1997) measured the RECD in 12 individuals aged between nine and 65 years who had a perforation of the eardrum. Compared to a control group of subjects with no middle ear pathology, the mean RECD was 9–12 dB lower at frequencies below 1500 Hz. The opposite affect occurs in an ear with middle ear effusion although the effect on ear canal SPL is much smaller. Martin et al. (1996) measured the RECD in 14 children aged between four and eight years with flat tympanograms and evidence of middle ear effusion on otoscopy. Compared to a control group, there was a mean increase in RECD of 3.5 dB around 1000 Hz. The opposite affect occurs in an ear with middle ear effusion although the effect on ear canal SPL is much smaller. Martin et al. (1996) measured the RECD in 14 children aged between four and eight years with flat tympanograms and evidence of middle ear effusion on otoscopy. Compared to a control group, there was a mean increase in RECD of 3.5 dB around 1000 Hz. Once again, the problem can be eliminated if the subject’s RECD is used to derive real ear SPL. A detailed discussion of the influence of impedance on ear canal SPL is provided by De Jonge (1996) and Voss et al. (2000).
Is It Necessary to Measure an RECD From Each Individual?

Numerous studies have revealed the extent by which the acoustic properties of the ear canal change during the first few years of life. As a child grows, the ear canal increases in volume and the RECD becomes smaller, especially at the higher frequencies. Figure 10 shows the RECD measured in a typical infant and adult. The difference at 3 kHz is in excess of 10 dB. It is also known that RECDs are highly variable for individuals within the same age range (Feigin et al. 1989; Bagatto, Scollie, Seewald, Moodie and Hoover 2002) so the actual difference for a given infant may be considerably higher. Bagatto et al. (2002) measured RECDs from a total of 392 subjects, spanning in age from one month to 16 years, when the ear canal was occluded with a personal earmold and an oto-admittance tip. Figure 11 shows the RECD values obtained at 4 kHz when using an oto-admittance tip. The largest RECD was measured at one month of age. However, it is difficult to predict what the RECD
will be for a given ear because of substantial inter-subject variability; for example, the range is 15 dB at one month of age and 25 dB over the first two years of life. For this reason it is advisable to measure the RECD for each infant. If the measurement cannot be completed then it will be necessary to resort to age-appropriate average values.

How Important is it to Measure an RECD from Each Ear?

Some subjects may show limited co-operation that is sufficient to obtain an RECD from one ear alone. How important is it to complete the measurement from both ears?

Munro and Buttfield (2004) compared the RECD from the right and left ear of a group of 18 normal hearing adult subjects whose ear canals were free from occluding wax and who had normal middle ear function as measured on tympanometry. The measurements were made with a personal earmold, foam eartip and oto-admittance tip. The mean difference between the right and left RECD was close to 0 dB for all earmold configurations. A cumulative frequency distribution of the difference between the right and left ear is shown in figure 12. Data for the personal earmolds, foam eartip and oto-admittance tip are shown in the top, middle and bottom panel respectively. The ordinate shows the percentage of subjects who had a difference between ears of less than 1 dB, 2 dB, 3 dB etc. For ease of illustration, the data have been restricted to 0.5, 1, 2 and 4 kHz. The difference between ears is usually less than 3 dB for most subjects. The study has yet to be extended to the clinical setting where subject cooperation and earmold fit may differ from these lab-based measurements. However, the results suggest that it may not always be necessary to measure an RECD from each ear if co-operation is limited. This finding is consistent with Tharpe, Sladen, Huta and McKinley Rothpletz (2001) who showed that, in a clinical setting, the difference on retesting the same ear is sufficiently high that it may mask differences between the right and left ear.

How Frequently Should the RECD be Measured?

The RECD will change over time for two reasons:

- the ear canal dimensions will increase with age;
- the fit of the personal earmold will change over time

The data from Bagatto et al. (2002) show that the largest changes in RECD occur within the first two years of life.
years of life. This suggests that the RECD should be measured frequently during the first few years of life. There have been no studies that have specifically addressed the frequency of measurement. Ideally, the RECD should be measured whenever the personal earmold is replaced although it is recognised that this may not always be possible. Clinical experience suggests that it may be sufficient to measure the RECD at three-month intervals until two years of age and then at six month intervals until five years of age.

Is the RECD Repeatable?

Many studies have shown that the test-retest difference in adults is very small and clinically acceptable. For example, Munro and Davis (2003) measured test/retest differences in a group of 16 cooperative adults and reported mean differences close to 0 dB with a standard deviation less than 1 dB.

Sinclair et al. (1996) carried out one of the few studies that have investigated test-retest variability in children. They studied 90 children (birth to seven years) and 10 adults. The mean difference on retest was less than 2 dB, irrespective of the age of the subject and the test frequency. The range of values across subjects was not reported although reliability coefficients were all positive and varied from 0.70 to 0.91 across age groups. Therefore, this study suggests that, in the hands of experienced clinicians, the RECD measurement is very repeatable. However, a less favourable outcome has been reported by Tharpe et al. (2001) who measured test-retest differences at various intervals throughout the first year of life in a group of 22 infants. The mean difference on retest was less than 1 dB; however, the standard deviations were typically around 2 dB from 0–6 months of age and 4 dB from 7–12 months of age. This would give a 95% range of approximately ± 4 dB and ± 8 dB respectively. These values are similar to those reported by Westwood and Bamford (1995) who measured the test-retest difference of the real ear aided response in 33 infants less than 12 months of age. Tharpe et al. performed measurements at every visit regardless of the state of the infant; therefore, there may have been occasions when it would have been appropriate to rely on average age-appropriate default values. This is an area that requires further investigation, especially in light of the rapid growth in newborn hearing screening and early intervention programs.

Is it Valid to Use the RECD to Derive Real-Ear SPL?

A number of studies have used the RECD to derive real ear SPL of audiometric data. Munro and Davis (2003) compared the measured and derived real-ear SPL of audiometer output in 16 adult subjects. The RECD was measured in the HA1 and HA2 2cc couplers with several insert earphone and earmold configurations. The mean difference between the measured and derived real-ear SPL was less than 1 dB and rarely exceeded 3 dB in any subject. Similar findings have been reported by Scollie, Seewald, Cornelisse and Jenstad (1998).

A number of studies have used the RECD to derive real ear SPL of electroacoustic data. Munro and Hatton (2000) compared the measured and derived real-ear SPL of hearing instrument output in 24 adult subjects. The RECD was measured with the ear canal occluded with three earmold configurations: personal earmold, disposable foam ear-tip and an oto-admittance tip. In addition, the test signal was presented via an insert earphone as well as via a loudspeaker in the sound field. When using the subject’s personal earmold, the mean difference between the measured and derived real-ear aided response was close to 1 dB and rarely exceeded 5 dB in any subject. Similar findings were reported by Seewald and Scollie (1999) who derived the real-ear aided response and the real-ear saturation response using the RECD.

The signal processed by a hearing instrument will normally produce a higher SPL in the ear canal than signals entering the ear canal directly via a vent in the earmold. However, there are occasions when this is not the case and the RECD procedure may yield invalid results. Hoover, Stelmachowicz and Lewis (2000) have shown this scenario to occur when the hearing instrument provides very little gain and there is a negative RECD. This may occur, for example, if the subject has good low frequency hearing and an open earmold. The derived ear canal SPL may underestimate the actual ear canal SPL.

With the exception of the relatively rare situation described by Hoover et al. (2000), the studies mentioned above have demonstrated that, if the RECD is measured with care, the derived real-ear SPL will be within a few decibels of the directly measured ear canal SPL obtained using in-situ audiometry or real-ear measurements.
Tips on Measuring the RECD

The importance of integrating the RECD into routine clinical practice has been recognised for many years. The emphasis on early intervention in permanent childhood hearing impairment means the importance of accounting for differences in external ear acoustics is more important than ever.

Perhaps the most difficult part of the RECD measurement procedure is the positioning of the probe tube within the ear canal. Provided the tip of the probe tube is extended more than 5 mm past the tip of the earmold then this is appropriate for frequencies up to 2 kHz. However, the tip of the probe tube is required to be positioned to within 5 mm of the eardrum if the clinician is interested in frequencies up to 6 kHz.

Tharpe et al. (2001) have investigated a number of practical considerations when measuring RECDs in infants. One consideration was the placement of the probe-tube within the ear canal. The study compared a constant insertion depth versus an acoustic method (inserting tip of probe tube beyond the 6 kHz standing wave ratio node) for placement of the probe tube. The results showed that there was little to be gained by using the more time-consuming acoustic insertion depth method.

Some real-ear systems use the standard coupler microphone for measuring the coupler SPL and the probe-tube microphone for measuring real-ear SPL. Because two different microphones are used, it is important that they are correctly calibrated with respect to each other. Ching and Dillon (2003) provide useful information on how to check the calibration of these microphones with reference to each other. Strategies to optimise RECD measurement have been provided by Bagatto (2001).

This article includes information on a variety of procedural issues such as correct probe-tube insertion depth. It also contains a useful section on troubleshooting.

Are There Any Questions Left to be Answered?

The clinical protocol for measuring the RECD assumes that the values obtained using the insert earphone can be applied to a coupler measurement performed with a hearing instrument. However, Munro and Salisbury (2002) have shown that the RECD is somewhat dependent on the measurement transducer. They compared the mean RECD obtained with two models of insert earphone in a group of 18 normally hearing adult subjects. The models of earphone used in the study were the EAR-Tone ER-3A and the Audioscan RE770. Measurements were made with a personal earmold and a foam eartip, and with three lengths of acoustic tubing. There was a mean difference between the RECDs measured with the two earphones of 9 dB at 1.5 kHz when the earmold tubing was around 40 mm in length. The difference was much smaller when the length of acoustic tubing was reduced. This finding may be clinically significant in adult subjects since the length of tubing in their personal earmold will usually be around 40 mm. An unpublished study by Caroline Bracewell and the author in our laboratory has replicated these findings for the ER-3A and RE770 earphones; interestingly, we have shown that the mean RECDs are similar when measured with an ER-3A and ER-5A earphone.

Although the RECD is normally measured using an insert earphone, the assumption is that the RECD can be applied to a coupler measurement performed with a hearing instrument. Until recently, no study had systematically compared the RECD measured with the ER-3A earphone and a hearing instrument. Munro and Toal (2005) compared the mean RECD measured with the ER3 insert earphone and two models of behind-the-ear (BTE) hearing instrument in 18 normally hearing adult subjects. Mean RECDs were measured using the HA1 and the HA2 2cc coupler and data were reported at 1/12 octave intervals from 0.2 to 6 kHz. Figure 13 shows the mean RECD measured with an insert earphone and the hearing instruments. The top panel shows the results using the HA1 2cc coupler and the bottom panel shows the results with the HA2 2cc coupler. Although the mean RECDs are similar for the three transducers, they are not the same. Differences occur in the mid-frequencies and this is most marked when the RECD has been measured using the HA2 2cc coupler.

In a recent study in our laboratory, Sarah Bant and I have extended the work of Munro and Toal (2005) by measuring the RECD with a wider range of BTE hearing instruments. RECDs were measured from 20 subjects (mean age 31 years) using the ER-3A earphone and five popular models of hearing instrument. The results show that there are differences in mean RECD across all the transducers. The mean
RECD measured with three models of BTE instrument were broadly similar but these were not the same as the insert earphone RECD: there were differences of up to 5 and 10 dB when using the HA1 and HA2 2cc coupler respectively.

The studies by Munro and Toal (2005) and Bant and Munro (unpublished) have shown that the RECD measured with an insert earphone may not always be representative of the differences in performance of a hearing instrument when measured in the real ear and the 2cc coupler. 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 (Sanborn 1998; Egolf, Feth, Cooper and Franks 1985; Gilman, Dirks and Stern 1981). Since the RECD is the difference between the 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 $Z_s$ and the impedance of the ear and coupler are taken as $Z_e$ and $Z_c$, respectively, then

$$RECD = \frac{(Z_e / Z_c) \times (Z_s + Z_c)}{(Z_s + Z_e)} \quad (1)$$

If $Z_s$ is much greater than either $Z_e$ or $Z_c$, this simplifies to

$$RECD = \frac{Z_e}{Z_c} \quad (2)$$

However, Sanborn (1998) and unpublished data from Sarah Bant and myself have 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 the 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 are smallest when using the HA1 2cc 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.

We are presently working with Phonak AG on modelling the RECD from acoustic impedance measurements of the transducers and real ear. For some transducers, including the ER-3A earphone, the model is within 2 dB of the measured RECD.

In the most recent of our RECD studies, Kerri Millward and I have compared the measured real-ear aided response (REAR) with the derived REAR obtained using the RECD measured with four models of BTE hearing instrument. There were 20 subjects (mean age 30 years), each having a personal earmold with 45 mm acoustic tubing. Unlike the earlier studies by Munro and Hatton (2000) and Seewald and Scollie (1999), we used both the HA1 and HA2 2cc coupler and analysed the findings in 1/12 octave intervals. The results show that there was a very good match between the measured and derived REAR when the RECD was measured with the subject’s hearing instrument: the mean difference was close to 0 dB and 95% of subjects were within 3 dB. However, when the REAR was derived using the RECD measured with an ER-3A earphone, there were differences of up to 5 and 10 dB for the HA1 and HA2 2cc coupler respectively. An example of the findings is shown in figure 14. The derived REAR was obtained using an RECD measured with the subject’s hearing instrument (open symbols) and the ER-3A insert earphone (filled symbols). In this example, the measured REAR lies directly beneath the open symbols (demonstrating that there is a very good match with the response that was derived using the RECD measured with the subject’s hearing instrument). However, there are clear differences from 1–3 kHz when the derived response was obtained using the RECD measured with the insert earphone. Some of these differences would have been missed if data analysis had been restricted to the main audiometric frequencies.

The results of our recent studies suggest that it may be appropriate to use the subject’s hearing instrument when measuring the RECD. Until recently, however, this has been difficult since it relies on sound field measures and these are influenced by the location of the probe tube reference microphone and movement of the infant during the measurement. These problems can be circumvented if sound field measurements are not required.

3 In our studies, the reference microphone for the probe tube assembly was modified so that it could be positioned directly beside the microphone of the hearing instrument.
Figure 13. The mean RECD measured with an ER3 insert earphone (grey circles) and two models of BTE hearing instrument. The RECD was measured using an HA1 2cc coupler (top panel) and an HA2 2cc coupler (bottom panel). From Munro and Toal (2005).
Figure 14. The mean derived REAR for a group of 20 adult subjects who were all fitted with the same model of BTE hearing instrument. The RECD used in the calculations was measured in an HA2 2cc coupler using the subject’s hearing instrument (open symbols) and the ER-3A insert earphone (filled symbols). The actual REAR that was measured directly with a probe-tube in the ear canal lies beneath the open symbols. The data come from an unpublished study by Millward and Munro.

One Way Forward

Phonak has developed the RECDdirect fitting tool for the Supero hearing instrument. The objective of the RECDdirect fitting tool is to rationalise the measurement procedure into a one-step process while minimising both measurement time and the need for additional equipment. There is no need for sound field measurement because the fitting software is used to generate a broadband noise that is delivered to the ear using the hearing instrument.

Munro and Toal (2004) compared the mean RECD measured with RECDdirect and with the conventional ER-3A earphone in 21 adult subjects. The mean RECDs are shown in figure 15. The results are very similar except at 2 kHz. The difference at 2 kHz is consistent with the transducer-dependent effects reported above.

Munro and Toal (2004) then measured how much the Supero 412 BTE hearing instrument deviated from DSL[io] target values for average speech using the ‘quick-fit’ (pre-fitting) option. The initial quick-fit settings were obtained for three different RECD values:

1. average default values for adults with an unvented earmold,
2. an individually measured RECD using the insert earphone, and
3. an individually measured RECD using RECDdirect.
Figure 15. Mean RECD measured using RECDdirect (filled circles) and insert earphone (open circles). The data comes from an unpublished study by Munro and Toal.

Figure 16. Median difference between DSL target and the measured real-ear responses for the default RECD (open triangles), insert earphone RECD (open circles) and RECDdirect (filled circles).
The hearing instrument was set to linear processing and to DSL targets for a flat hearing impairment of 50 dB HL. The program selector, noise canceller and volume control were all deactivated. For the individually-measured RECDs, a new probe tube was calibrated and inserted 30 mm past the tragus for each subject.

The ability of each of the fittings to meet the DSL target for amplified speech was measured using an Audioscan RM500 real ear measurement system. The real ear aided response (REAR) was measured with a speech weighted pure tone. The reference microphone was positioned next to the hearing instrument microphone during the measurement.

A comparison of the DSL target and the median real ear response is shown in figure 16. The median difference is small for all conditions, especially when the RECD has been individually measured (insert earphone or RECDdirect). The match to target was then inspected for individual subjects. The 95% range is shown in figure 17. The deviation was almost always within 5 dB of the DSL target, irrespective of which RECDs were used in the pre-fitting calculations. However, the best match to DSL targets (for median and individual subjects) was obtained when the pre-fitting settings were calculated using RECDdirect. These data suggest that the RECDdirect fitting tool is a valid procedure for selecting the initial settings of the hearing instrument. The actual real-ear SPL can be verified in the usual manner by adding the RECD values (obtained with RECDdirect) to the 2cc coupler response of the hearing instrument. Finally, despite the success of the RECDdirect fitting method in the above study, it does not replace the need for an RECD obtained with an insert earphone when deriving the real-ear SPL of audiometric data.

**Conclusions**

The acoustics of the external ear differ significantly between infants and adults and from one infant to another. These differences have important implications for audiometric assessment and hearing instrument fitting. The solution is to integrate the RECD measurement into the assessment and fitting process for infants and children. A simple and efficient procedure for measuring the RECD has been available for many years. The results of recent studies using adult subjects suggest that there may be occasions when it is appropriate to use the subject’s own

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4 In order to make a valid comparison with the DSL target values, a correction for microphone location effects was added to the measured real ear aided response since this was measured with a reference microphone positioned close to the hearing instrument.
hearing instrument to measure the RECD instead of using an insert earphone. Recent developments such as the RECDdirect fitting tool can overcome the difficulties associated with sound field measurements.

Acknowledgements

We are indebted to Etymonic Design Inc. (manufacturer of the Audioscan RM500 and Verifit), PC Werth Ltd, and Phonak for supporting our program of RECD research.

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