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Real-Ear-to-Coupler Difference Predictions as a Function of Age for Two Coupling Procedures

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Abstract

The predicted real-ear-to-coupler difference (RECD) values currently used in pediatric hearing instrument prescription methods are based on 12-month age range categories and were derived from measures using standard acoustic immittance probe tips. Consequently, the purpose of this study was to develop normative RECD predicted values for foam/acoustic immittance tips and custom earmolds across the age continuum. To this end, RECD data were collected on 392 infants and children (141 with acoustic immittance tips, 251 with earmolds) to develop normative regression equations for use in deriving continuous age predictions of RECDs for foam/acoustic immittance tips and earmolds. Owing to the substantial between-subject variability observed in the data, the predictive equations of RECDs by age (in months) resulted in only gross estimates of RECD values (i.e., within ± 4.4 dB for 95% of acoustic immittance tip measures; within ± 5.4 dB in 95% of measures with custom earmolds) across frequency. Thus, it is concluded that the estimates derived from this study should not be used to replace the more precise individual RECD measurements. Relative to previously available normative RECD values for infants and young children, however, the estimates derived through this study provide somewhat more accurate predicted values for use under those circumstances for which individual RECD measurements cannot be made.

Key Words: Amplification for children, predicted values, real-ear-to-coupler difference, real-ear measurements

Abbreviations: BTE = behind the ear; RECD = real-ear-to-coupler difference

Sumario

Los valores predictivos de la diferencia oido real a acoplador (RECD) utilizados en los métodos de prescripción de instrumentos auditivos pediátricos están basados en categorías con un rango de edades de 12 meses, y se derivaron de mediciones utilizando olivas convencionales de impedanciometría. Consecuentemente, el propósito de este estudio fue el de desarrollar valores normativos de predicción de RECD para olivas impedanciométricas convencionales de espuma y para moldes auditivos hechos a la medida a lo largo de todo el espectro de edades. Las RECD fueron colectadas en 392 infantes y niños (141 con olivas de impedanciometría y 251 con moldes auditivos) para desarrollar ecuaciones normativas de regresión que pudieran ser utilizadas en derivar predicciones de RECD para las distintas edades, tanto para dichas olivas y como para los moldes. Debido a la sustancial variabilidad entre sujetos que se observó en la información recogida, las ecuaciones predictivas para RECD por edad (en meses) rindieron sólo estimados gruesos de estos valores de RECD (p. ej., dentro de ± 4.4 dB para el 95% de las medidas en olivas de impedanciometría; dentro de ±5.4 dB para el 95% de las medidas en moldes auditivos a la medida) en las diferentes frecuencias. Así, se concluye que los estimados derivados de este estudio no deben usarse en sustitución de las medidas precisas e individuales de RECD. Sin embargo, en relación a los valores normativos de RECD previamente disponibles para niños pequeños, los estimados que se derivan de este estudio aportan valores predictivos más exactos, que pueden ser usados en aquellas circunstancias en las cuales las medidas individuales de RECD no pueden realizarse.

Palabras Clave: Amplificación para niños, valores predictivos, diferencia de oído real a acoplador, medidas de oído real o de inserción real

Abreviaturas: BTE = retroauricular; RECD = diferencia de oído real a acoplador

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Real-ear-to-coupler difference (RECD) values for infants and young children are known to vary significantly from average adult values and are highly variable between infants and children of the same age (Feigin et al, 1989; Seewald and Scollie, 1999). For these reasons, it has been recommended that clinicians measure an RECD for individuals, especially infants and children, as part of the hearing aid selection and fitting process (Moodie et al, 1994; Seewald et al, 1999).

In 1994, Moodie and colleagues reported the development of a clinical RECD measurement procedure for application with infants and young children. They proposed that the measurement procedures they described could be used to determine an individualized acoustic transform for use with formal electroacoustic fitting procedures such as the Desired Sensation Level (DSL) method (Moodie et al, 1994; Seewald, 1995). More specifically, they suggested that in combination with a given electroacoustic fitting algorithm, the individual's measured RECD values can be used to generate the appropriate 2-cc coupler gain and output response for a hearing instrument. Recent studies have shown the clinical RECD procedure originally reported by Moodie and colleagues (1994) to be highly repeatable and valid for the purposes of hearing aid fitting in infants and children (Sinclair et al, 1996; Seewald et al, 1999; Munro and Hatton, 2000). Circumstances may exist, however, that prevent an RECD measurement from being performed. Some real-ear equipment may not be designed for such measurement, or an uncooperative child may prevent the measurement from being completed. In such cases, average values are available in prescriptive software systems. For example, the DSL [i/o] version 4.1 software (Cornelisse et al, 1995) provides age-appropriate RECD values (Bentler and Pavlovic, 1989; Feigin et al, 1989).

The mean RECD values for infants and children reported by Feigin and colleagues (1989) were derived from probe-tube microphone measures of ear canal sound pressure levels obtained from 31 children under 5 years of age using acoustic immittance probe tips. In reporting the mean RECD values as a function of age, Feigin and colleagues divided their sample into five age groups: 0 to 12 months, 13 to 24 months, 25 to 36 months, 37 to 48 months, and 49 to 60 months. Values for each of these age groups are used in the current version of DSL [i/o] software for predicting RECDs for infants and children.

Using average age-appropriate RECD values is more desirable than using a set of average adult values for infants and young children. The age-appropriate average values reported by Feigin and colleagues (1989), however, currently used in most hearing instrument fitting systems, are limited in two ways. First, Feigin and colleagues used acoustic immittance probe tips to measure the RECD. Most infants and young children will be fitted with behind-the-ear (BTE) hearing instruments requiring a custom earmold. Therefore, the use of average RECD values derived from probe tip RECD measures may result in inaccurate RECD predictions for the conditions under which the infant/child will actually be fitted using a custom earmold.

A second limitation of the average RECD values reported by Feigin and colleagues (1989) is that they are defined as a function of age into 12-month categories. Consequently, when applied clinically, the same set of average RECD values would be used for all infants/children within the same category. For instance, identical predicted RECD values would be applied for a 1-month-old infant and for an 11-month-old infant.

Recently, Tharpe (2000) surveyed 425 pediatric audiologists to determine what procedures they used in pediatric hearing instrument selection and fitting. Her findings showed that, when selecting hearing instrument output limiting characteristics, the majority of participating audiologists reported using average RECD values. Several studies have demonstrated the accuracy, efficiency, and validity of using an RECD measurement in the hearing aid fitting process (Sinclair et al, 1996; Scollie et al, 1998; Seewald et al, 1999; Munro and Hatton, 2000). However, as indicated by the findings of Tharpe's survey, there are many instances in which pediatric audiologists are routinely using predicted rather than measured RECD values in the hearing aid fitting process. In view of this finding, it is important to develop RECD predictions for infants and young children that can lead to the greatest degree of fitting accuracy possible when average values must be used. Consequently, this study was designed to develop normative predictions for foam/acoustic immittance tip and earmold RECDs from a relatively large sample of subjects across the relevant age continuum.

METHOD

Subjects

Subjects were recruited from the University of Western Ontario Hearing Clinic (London, Ontario, Canada) and the Boys Town National Research Hospital Audiology Department (Omaha, Nebraska). A total of 392 subjects participated in the study with an age range of 1 month to 16 years and a mean age of 50.7 months. RECD measurements were obtained from 141 ears with probe tips designed for immittance measures (age range = 1 month to 6.8 years; mean = 32.5 months). Measurements of the RECD were obtained from 251 ears using the child's personal earmold (age range = 2 months to 16.4 years; mean = 60.9 months). The number of subjects per age group for RECDs measured with acoustic immittance tips and custom earmolds is shown in Table 1.

Table 1 Number of Subjects per Age Group for RECDs Measured with Acoustic Immittance Tips and Custom Earmolds

	Number of Subjects	
Age Group	*Tip*	*Earmold*
< 7 mo	22	14
7–12 mo	16	26
1–2 yr	28	36
2–3 yr	18	20
3–4 yr	12	29
4–5 yr	15	27
> 5 yr	30	99

RECD = real-ear-to-coupler difference.

Procedure

Pediatric audiologists who have extensive experience performing RECD measurements on infants and young children made the measurements. RECDs were measured only on subjects with both normal otoscopic and acoustic immittance results. All RECD measurements were obtained using a Fonix 6500 hearing aid analyzer following the procedure described by Moodie and colleagues (1994). Briefly, the probe microphone was substituted for the standard ½" microphone and the probe tube was attached to the HA-2 coupler for the 2-cc coupler response. After daily calibration, the Fonix speech-weighted composite noise test signal was delivered through an ER-3A insert earphone to the coupler at a level of 50 dB SPL and the coupler response was measured by the probe microphone. For the real-ear canal response, the probe tube was inserted into the ear approximately 5 mm from the tympanic membrane. Earmold lubricant was applied to the medial portion of the probe tube before insertion to reduce friction when the tip or earmold was inserted into the ear. Probe tube insertion depth was controlled by marking the tube 15 to 20 mm from the medial tip, depending on the age of the child and the clinician's judgment (Sinclair et al, 1996). The probe tube was inserted until the mark reached the subject's intertragal notch. Proper probe tube placement was confirmed using otoscopy and further adjustments were made as necessary.

The findings of a previous study by Frank and Vavrek (1992) suggested that a portion of their adult subjects had ear canals that were too small for the insertion of foam tips to the recommended insertion depth. Consequently, acoustic immittance tips were used in this study, coupled to the EarTone ER-3A insert phone transducer via an acoustic immittance tip adapter (ER3-06). Acoustic immittance tips come in a variety of sizes, which facilitates successful insertion into small ear canals. On the basis of some previous findings by Borton and colleagues (1989), it was assumed that the RECD measurement using either foam or immittance tips would result in essentially the same values across frequencies.

The subjects' personal earmolds were unvented and were made of standard silicone earmold material and had #13 tubing. The acoustic immittance tip or earmold was coupled to the insert phone and placed in the ear canal. The acoustic immittance tips used in this study had a standard cuff length of 6 mm. Insertion depth was controlled by inserting the tip such that the lateral end of the cuff was flush with the opening of the ear canal. The lubricant on the probe tube helped reduce slit leaks from the tip or earmold by creating a seal between it and the subject's ear canal. To ensure that the probe tube remained at the appropriate depth during insertion of the tip or earmold, the clinician verified that the mark on the tube remained at the intertragal notch. The 50 dB SPL speech-weighted composite signal was presented through the insert earphone and the real-ear response was measured. The difference in dB between the real-ear response and the coupler response for the same test signal defined the RECD across frequencies for each subject. For clinical purposes, Bagatto (2001) has described a set of procedures and some clinical strategies for making RECD measures with infants and young children.

RESULTS AND DISCUSSION

This experiment was designed to develop normative predictions for foam/acoustic immittance tip and custom earmold RECDs as a function of age. Logarithmic regression analyses were performed on the acoustic immittance tip and earmold RECD data separately, at nine audiometric frequencies, to develop two sets of predictive equations. Statistically, the logarithmic regression analysis provided significantly better fits to the data than linear regression analysis at 13 of 18 frequencies ($p < .05$). The significance values for the logarithmic regression estimates are presented for each frequency for both acoustic immittance tips and custom earmolds in Tables 2 and 3, respectively.

For both the acoustic immittance tip and custom earmold RECDs, logarithmic regression coefficients were obtained at each of nine octave and interoctave audiometric frequencies for use in the following equation:

$$Y = b_0 + [b_1 * \ln(t)]$$

where Y represents the RECD value, in dB, for each frequency, in Hz, b_0 represents the y-intercept, b_1 represents the slope, and t represents the age in months.

Acoustic Immittance Tip RECDs

The acoustic immittance tip RECD values are plotted as a function of age in Figure 1 for each of four frequencies. By convention, all positive values plotted in this figure indicate the extent to which the dB SPL measured in the real ear exceeded the dB SPL that was measured in the HA-2 2-cc coupler. The line on each scatter plot indicates the logarithmic regression represented by the equation for that frequency. Two observations can be made for the RECD data that are plotted in Figure 1. First, for any given age, substantial between-subject variability is observed in these data at the four frequencies shown. For example, for RECDs in infants less than 6 months of age (N = 22), the range of variability was 16 dB at 500 Hz and 14 dB at 2000 Hz. The between-subject variability at the five remaining frequencies (data not shown) was similarly large. Second, the results of the logarithmic regression analyses suggest that for the higher frequencies (e.g., 2000 and 4000 Hz), the greatest rate of change in the RECD values occurs within the first 10 to 12 months of life.

The regression coefficients and r^2 values for each frequency for the RECD acoustic immittance tip data are displayed in Table 2 as a function of frequency. The r^2 values shown in this table indicate at best a weak and, in some cases, nonexistent association between the measured RECD values and subject age. For the acoustic immittance tip data obtained in this study, the r^2 values ranged from a low of .00 at 500 Hz to a high of .32 at 4000 Hz.

The difference, in dB, between the measured and predicted RECD value (using the logarithmic regression coefficients shown in Table 2) was calculated at each frequency for each subject. The mean (unsigned) absolute error values associated with the RECD predictions for acoustic immittance tips are shown in Table 4, along with the 95 percent confidence interval around the mean as a function of frequency. Results showed that the average unsigned error ranged from a low of 2.2 dB at 750 Hz to a high of 4.0 dB at 6000 Hz. On average, the acoustic immittance tip RECD values were predicted to within ± 4.4 dB in 95 percent of the cases across frequencies, with the range of predicted RECD

Table 2 Logarithmic Regression Coefficients, r^2 Values, and Significance (p) Values for the RECDs Measured with Acoustic Immittance Tips as a Function of Frequency

	Frequency (Hz)								
	250	*500*	*750*	*1000*	*1500*	*2000*	*3000*	*4000*	*6000*
Slope	−0.35	0.05	−0.20	−0.43	−0.58	−0.68	−1.56	−2.00	−2.04
y-intercept	−0.31	3.12	6.28	8.82	8.69	9.74	12.20	16.57	16.38
r^2	.01	.00	.01	.03	.04	.06	.28	.32	.18
p	.29	.82	.31	.04*	.02*	.00*	.00*	.00*	.01*

*Significant p value with $\alpha = .05$.
RECD = real-ear-to-coupler difference.

Table 3 Logarithmic Regression Coefficients, r^2 Values, and Significance (p) Values for the RECDs Measured with Custom Earmolds as a Function of Frequency

	Frequency (Hz)								
	250	*500*	*750*	*1000*	*1500*	*2000*	*3000*	*4000*	*6000*
Slope	0.74	0.25	−0.46	−0.99	−1.00	−1.04	−2.40	−2.22	−3.03
y-intercept	−2.34	4.09	8.80	12.64	14.12	13.81	16.46	15.23	17.08
r^2	.02	.00	.01	.07	.10	.12	.32	.22	.20
p	.02*	.35	.06	<.001*	<.001*	<.001*	<.001*	<.001*	<.001*

*Significant p value with α = .05.
RECD = real-ear-to-coupler difference.

values as small as 3.1 dB at 750 Hz and as great as 6.3 dB at 6000 Hz.

By examining the 95 percent confidence intervals in Table 4, it can be seen that acoustic immittance tip RECDs can be predicted with somewhat greater accuracy within the mid-frequency range (750–3000 Hz). In contrast, the 95 percent confidence intervals are roughly twice as large at the lowest (250 Hz) and highest (6000 Hz) frequencies included in the analysis. Thus, depending on the frequency of interest, the actual acoustic immittance tip RECD can be predicted to fall within a range of 6 dB (at 750 Hz) at best and 13 dB (at 6000 Hz) at worst in 95 percent of cases. These findings support the position that an infant/young child's RECD should be measured and not predicted whenever possible.

Measurement error may contribute to increased variability at the lowest and highest frequencies. Greater variability in the low frequencies may be associated with acoustic leak-

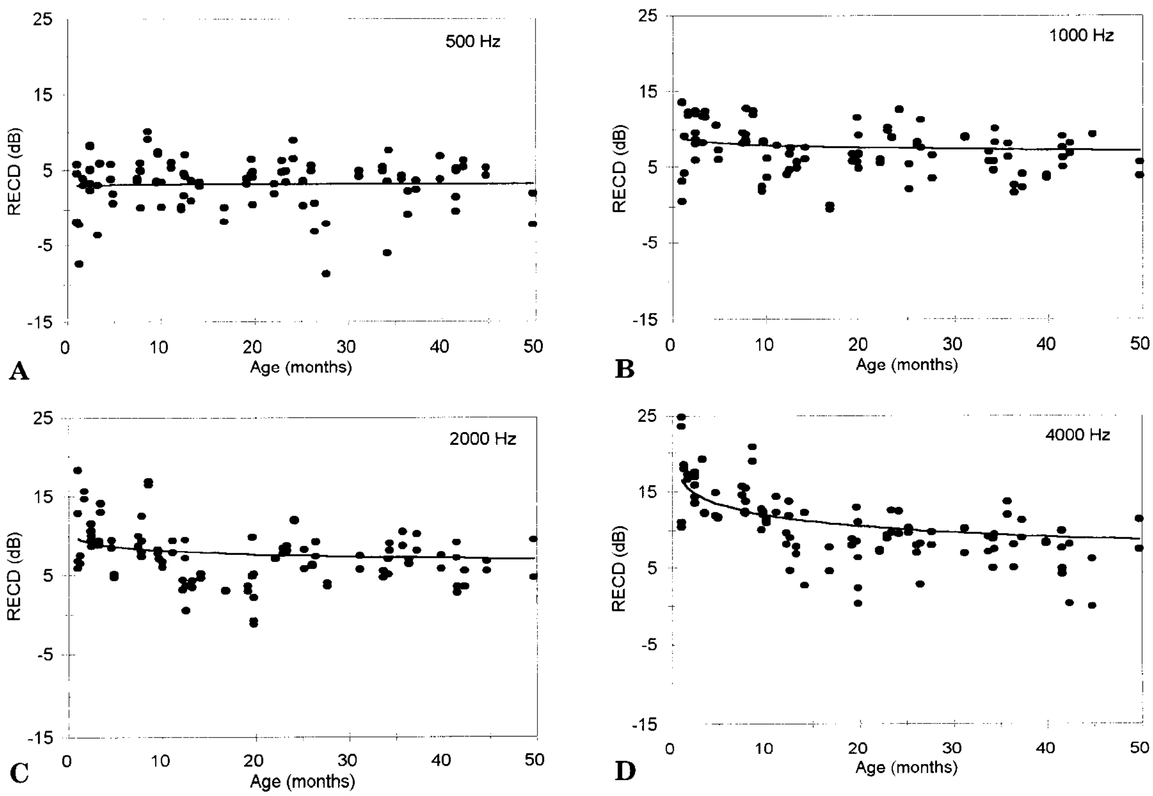

Figure 1 Real-ear-to-coupler differences (RECDs) (in dB) measured with acoustic immittance tips and plotted as a function of age (in months) and frequency. Data for four frequencies are plotted in each panel as follows: *A*, 500 Hz; *B*, 1000 Hz; *C*, 2000 Hz; and *D*, 4000 Hz. The *solid line* indicates the regression represented by the prediction equation derived from the data at each frequency.

Table 4 Averaged Unsigned Error and 95% Confidence Intervals (CI) of Predicted RECD Values for Acoustic Immittance Tips as a Function of Frequency

	Frequency (Hz)								
	250	*500*	*750*	*1000*	*1500*	*2000*	*3000*	*4000*	*6000*
Average unsigned error (dB)	3.4	2.5	2.2	2.3	2.6	2.3	2.3	2.6	4.0
95% CI (dB)	±6.2	±4.2	±3.1	±3.6	±4.3	±4.1	±3.7	±4.5	±6.3

RECD = real-ear-to-coupler difference.

age during the measurement (de Jonge, 1996). At high frequenices, the variability may be a result of probe tube insertion depth. Measurements of eardrum SPL in the high frequencies are sensitive to depth of probe tube insertion and vertical placement of the tube relative to the eardrum (Chan and Geisler, 1990). In a study by Sinclair and colleagues (1996), repeatability of RECD measures was found to be poorest at the very low (300 Hz) and very high (4000 Hz) frequencies. The present data indicate a similar pattern of variability, which can be associated with potential measurement errors.

Custom Earmold RECDs

The RECD values obtained with custom earmolds are plotted as a function of age in Figure 2 at four test frequencies. Similar to the acoustic immittance tip data plotted in Figure 1, the RECD values for custom earmolds plotted in Figure 2 reveal substantial between-subject variability across the age continuum. For example, for infants less than 6 months of age involved in this portion of the study (N = 14), the range of variability in RECD values at 500 and 2000 Hz was 15 dB and 9 dB, respectively.

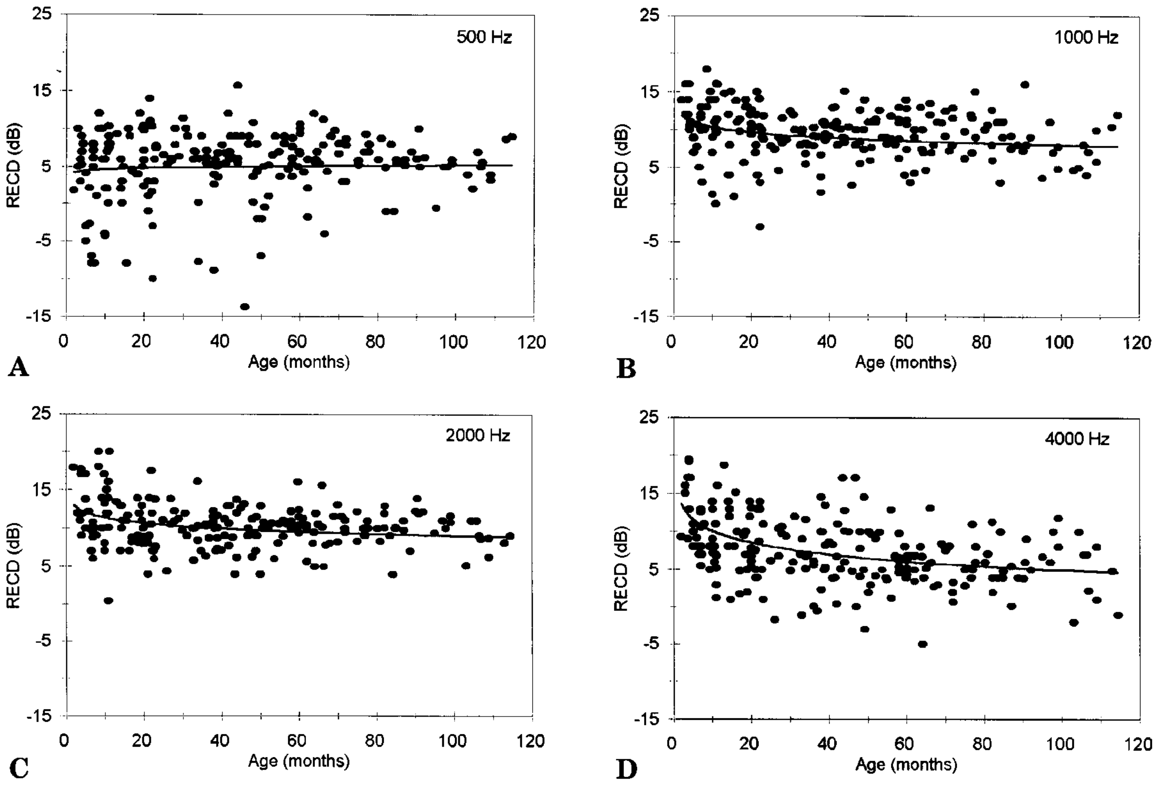

Figure 2 Real-ear-to-coupler differences (RECDs) (in dB) measured with custom earmolds and plotted as a function of age (in months) and frequency. Data for four frequencies are plotted in each panel as follows: *A*, 500 Hz; *B*, 1000 Hz; *C*, 2000 Hz; and *D*, 4000 Hz. The *solid line* indicates the regression represented by the prediction equation derived from the data at each frequency.

In addition, the results of the logarithmic regression analyses indicate that the greatest rate of change in the mean RECD values occurs within the first year of life. This finding can be most clearly observed in these custom earmold RECD data at 4000 Hz.

The regression coefficients and r^2 values for each frequency for RECDs with earmolds are presented in Table 3 as a function of frequency. Again, similar to the r^2 values for the acoustic immittance tip data, the r^2 values shown in Table 3 indicate a weak and, in some cases, nonexistent association between the measured RECDs and subject age. For the custom earmold data obtained in this study, the r^2 values ranged from a low of .00 at 500 Hz to a high of .32 at 3000 Hz.

The difference, in dB, between the measured and predicted earmold RECD value (using the logarithmic regression coefficients in Table 3) was calculated at each frequency across age. Table 5 shows the mean (unsigned) absolute error values associated with the RECD predictions for earmolds, along with the 95 percent confidence interval as a function of frequency. Results showed that the average unsigned error ranged from a low of 2.2 dB at 2000 Hz to a high of 5.0 dB at 6000 Hz. On average, the RECD values were predicted to within ± 5.4 dB in 95 percent of the cases across frequencies, with the range of predicted RECD values as small as 3.8 dB at 2000 Hz and as great as 7.6 dB at 6000 Hz.

The 95 percent confidence intervals shown in Table 5 are slightly wider than those calculated for the acoustic immittance tip data. Again, it appears that RECD values can be predicted with somewhat greater accuracy within the mid-frequency range (750–3000 Hz). It can be seen that even at these frequencies, however, the average range in which 95 percent of cases with custom earmolds fell is on the order of 10 dB. For the test frequencies above 3000 Hz and below 750 Hz, the average range in which 95 percent of cases fell in this sample approached 14 dB. Clearly, these findings underscore the need to measure the RECD, for the purposes of precise electroacoustic hearing instrument fitting in pediatric cases, whenever possible.

Effects of Slit Leak Venting

In an attempt to quantify the measurement error associated with acoustic leakage, a systematic data adjustment procedure was applied. Acoustic leakage will result in RECD values below zero in the low-frequency region (de Jonge, 1996). Therefore, negative RECD values at 250 and 500 Hz were considered outliers and coded as missing data in both data sets (Tabachnick and Fidell, 1996). Values of zero and above remained in the original data sets. A logarithmic regression analysis was performed to generate a new set of coefficients for acoustic immittance tips and earmolds with the adjusted data. Acoustic immittance tip RECD values predicted using the new coefficients resulted in an average difference of 3.7 dB at 250 Hz and 2.4 dB at 500 Hz compared with values generated using the original coefficients. For predicted earmold RECD values, the average difference was 3.5 dB at 250 Hz and 2.6 dB at 500 Hz. These differences are similar to the test–retest reliability of individually measured RECDs (Sinclair et al, 1996). Therefore, the measurement error associated with acoustic leakage in this data set is not likely to have a significant effect on the resulting RECD predictions and their application in the hearing aid fitting.

Individual measurement of the RECD remains very important for capturing specific ear canal acoustics, especially in the high-frequency region. As stated earlier, slit leak venting affects the low-frequency region. Therefore, clinicians should examine each RECD measurement for slit leaks and attempt to eliminate them by adjusting the real-ear setup (Bagatto, 2001). If a slit leak cannot be resolved, the clinician may apply

Table 5 Average Unsigned Error and 95% Confidence Intervals (CI) of Predicted RECD Values for Custom Earmolds as a Function of Frequency

	Frequency (Hz)								
	250	*500*	*750*	*1000*	*1500*	*2000*	*3000*	*4000*	*6000*
Average unsigned error (dB)	3.8	3.1	2.7	2.5	2.3	2.2	2.7	3.3	5.0
95% CI (dB)	±6.7	±6.0	±5.6	±5.1	±4.1	±3.8	±4.8	±5.3	±7.6

RECD = real-ear-to-coupler difference.

the average adjusted RECD predicted values derived from this study. For an RECD measured using an acoustic immittance tip, negative values at 250 and 500 Hz can be replaced with 2.4 and 4.3 dB, respectively. Negative low-frequency values from an earmold RECD can be substituted with 3.2 dB at 250 Hz and 6.1 dB at 500 Hz. In situations in which acoustic leakage in an RECD measurement is inevitable, replacing the negative low-frequency values with the average adjusted RECD predicted values is a reasonable alternative. This method will also maintain the individually measured RECD values in the mid- and high-frequency regions.

Effects of Acoustic Venting

The data reported in this article were gathered from unvented earmolds. Therefore, it is not possible to assess or predict the effects of vent diameter on the RECD from these data. Some BTE hearing aid fittings require acoustic venting in the earmold for a customized fit. The reader is referred to Hoover et al (2000) for further details regarding the effects of earmold vents on RECD values and their application to hearing aid fittings.

Effects of Middle Ear Status

Finally, we remind the reader that the RECD measurements used to develop the prediction equations in this study were performed on infants and children with normal middle ear function. It is well known that the status of the middle ear can affect external ear canal acoustics (e.g., Martin et al, 1996; Voss et al, 2000). Specifically, the increased mass and stiffness of a fluid-filled ear will result in a greater sound pressure level reflected by the tympanic membrane and consequently will result in an increase in the RECD values in the low- and mid-frequency regions compared with a measurement obtained in an ear without middle ear effusion (Martin et al, 1996). In addition, a perforated eardrum will result in negative RECD values (e.g., −10 to −15 dB) in the low-frequency (250–500 Hz) region (Martin et al, 1997; Voss et al, 2000). It is, of course, important to define and account for these acoustic effects when selecting and fitting a hearing instrument. Therefore, in cases in which middle ear dysfunction is suggested, measuring the child's RECD will provide a more accurate representation of the child's ear canal acoustics than using predicted values in the amplification selection and fitting process.

SUMMARY AND CONCLUSIONS

It is known that using a measured RECD is a valid and reliable way to estimate the real-ear response characteristics of hearing instruments (Seewald et al, 1999). However, during the process of selecting and fitting amplification in infants and young children, RECD measures may not always be possible. This study developed equations for use in predicting RECD values across frequency for a variety of ages to the nearest month, whereas the RECD predictions documented in the current literature are based on age ranges of 12 months. In addition, equations have been developed to predict RECDs for an earmold coupling technique, whereas previous estimates have been for acoustic immittance tip coupling. Thus, in cases in which an RECD measurement cannot be obtained with an infant or young child, use of the appropriate set of RECD predictions developed through this study may be substituted.

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