9-18-2023

Validation of an integrated pressure level measured earmold wideband real-ear-to-coupler difference measurement

Matthew Urichuk
Western University, murichuk@uwo.ca

David Purcell
Western University, purcelld@nca.uwo.ca

Prudence Allen
Western University, pallen@uwo.ca

Susan Scollie
Western University, scollie@nca.uwo.ca

Citation of this paper:
Matthew Urichuk, David Purcell, Prudence Allen & Susan Scollie (18 Sep 2023): Validation of an integrated pressure level measured earmold wideband real-ear-to-coupler difference measurement, International Journal of Audiology, DOI: 10.1080/14992027.2023.2254934

International Journal of Audiology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/iija20

Validation of an integrated pressure level measured earmold wideband real-ear-to-coupler difference measurement

Matthew Urichuk, David Purcell, Prudence Allen & Susan Scollie

To cite this article: Matthew Urichuk, David Purcell, Prudence Allen & Susan Scollie (18 Sep 2023): Validation of an integrated pressure level measured earmold wideband real-ear-to-coupler difference measurement, International Journal of Audiology, DOI: 10.1080/14992027.2023.2254934

To link to this article: https://doi.org/10.1080/14992027.2023.2254934

INTERNATIONAL JOURNAL OF AUDIOLOGY
https://doi.org/10.1080/14992027.2023.2254934

ORIGINAL ARTICLE

Validation of an integrated pressure level measured earmold wideband real-ear-to-coupler difference measurement

Matthew Urichuk[a,b], David Purcell[a,b,c], Prudence Allen[a,b,c] and Susan Scollie[a,b,c]

[a]Faculty of Health Sciences, School of Communication Sciences and Disorders, Western University, London, Ontario, Canada; [b]Faculty of Health Sciences, Health and Rehabilitation Sciences Graduate Program, Western University, London, Ontario, Canada; [c]Faculty of Health Sciences, National Center for Audiology, Western University, London, Ontario, Canada

ABSTRACT

Objective: To validate measurement of predicted earmold wideband real-ear-to-coupler difference (wRECD) using an integrated pressure level (IPL) calibrated transducer and the incorporation of an acoustically measured tubing length correction.
Design: Unilateral earmold SPL wRECD using varied hearing aid tubing length and the proposed predicted earmold IPL wRECD measurement procedure were completed on all participants and compared.
Study Sample: 22 normal hearing adults with normal middle ear status were recruited.
Results: There were no clinically significant differences between probe-microphone and predicted earmold IPL wRECD measurements between 500 and 2500 Hz. Above 5000 Hz, the predicted earmold IPL wRECD exceeded earmold SPL wRECDs due to lack of standing wave interference. Test-retest reliability of IPL wRECD measurement exceeded the reliability of earmold SPL wRECD measurement across all assessed frequencies, with the greatest improvements in the high frequencies. The acoustically measured tubing length correction largely accounted for acoustic effects of the participant's earmold.
Conclusions: IPL-based measurements provide a promising alternative to probe-microphone earmold wRECD procedures. Predicted earmold IPL wRECD is measured without probe-microphone placement, agrees well with earmold SPL wRECDs and is expected to extend the valid bandwidth of wRECD measurement.

ARTICLE HISTORY
Received 17 March 2023
Revised 18 August 2023
Accepted 24 August 2023

KEYWORDS
RECD; IPL; hearing aids; real ear measurement

1. Introduction

An individual's hearing aid response needs to be measured and verified reliably while accounting for significant variability caused by their unique ear-canal and middle ear properties to ensure safe and beneficial amplification (AAA 2013; Valente 2006; Saunders and Morgan 2003; McCreery et al. 2015; Scollie et al. 1998; Watts et al. 2020). One method to account for this variability is the real-ear aided response (REAR; American National Standards Institute (ANSI) 2013). The REAR can be measured directly or estimated using the transform for estimating real ear output (TEREO; Seewald et al. 1997; Mueller and Hall 1998), which accounts for both microphone location effects and the individual's real-ear to coupler difference (RECD; American National Standards Institute (ANSI) 2013; Bagatto et al. 2005). The RECD measurement can be made in seconds and does not require sustained participation from the patient, making it a recommended choice for hearing aid verification in infant populations, remote fittings, and situations where REAR measurement may not be possible (Moodie, Seewald, and Sinclair 1994; Moodie, Pietrobon, et al. 2016; AAA 2013).

Measurement of the RECD can be done using either a foam-tip transducer or the individual's personalised earmold. The RECD measured with a personal earmold does not meet the standard definition of the RECD (American National Standards Institute (ANSI) 2013) and is instead considered an Ear to Coupler Level Difference (ECLD), although this measure may be labelled as an "RECD" in clinical equipment, mainly due to use of legacy terminology. Earmold "RECDs" are necessary, however, to predict the on-ear responses for behind-the-ear (BTE) hearing aids due to the effects of earmold acoustics. This can help to ensure accurate hearing aid fitting at frequencies up to 4000 Hz (Munro and Davis 2003; Munro and Hatton 2000; Vaisberg et al. 2018).

Above 4000 Hz, probe-microphone RECD measurements become less accurate and less reliable due to reflected wave interference introducing up to 20 dB of variability into probe-microphone measurements (Chan and Geisler 1990; McCreery et al. 2009). Standing wave interference limits the valid bandwidth of both direct REAR and RECD measurement (Bagatto et al. 2005; Feigin et al. 1989; Munro and Hatton 2000; Tharpe et al. 2001; Vaisberg et al. 2018; Valente et al. 1994). Minimising standing wave errors in the RECD has been of interest previously and led to the development of the wideband RECD (wRECD; International Electrotechnical Commission (IEC) 2016). The wRECD uses a 0.4 cc coupler instead of a traditionally used 2.0 cc coupler and improves the validity of the coupler measurement at high frequencies (Vaisberg et al. 2018). However, the wRECD does not mitigate the $^3/_4$-wavelength standing wave errors in the ear-canal measurement. This may limit the accuracy of hearing aid verification procedures that incorporate the wRECD in the extended high-frequency range (>8000 Hz).

CONTACT Matthew Urichuk urichukm@myumanitoba.ca National Centre for Audiology, 1201 Western Rd., London, Ontario N6G 1H1, Canada
Supplemental data for this article can be accessed online at https://doi.org/10.1080/14992027.2023.2254934.

Historically, hearing aids have provided only limited high-frequency (i.e. >2000-4000 kHz) functional gain, however, technological developments continue to expend the bandwidth of hearing aids to extended high frequencies (Moore, Stone, and Alcantara 2001, Moore et al. 2008). Such technological advances are important as extended hearing aid bandwidths improve speech recognition, sound quality, and listener preference (Alexander and Rallapalli 2017; Brennan et al. 2014; Folkeard et al. 2021; Füllgrabe et al. 2010; Hornsby, Johnson, and Picou 2011; Levy et al. 2015; Ricketts, Dittberner, and Johnson 2008; Vaisberg et al. 2021; Vaisberg et al. 2021; Van Eeckhoutte et al. 2020). Furthermore, some prescriptive methods provide targets for audibility at 8000 Hz and above, which further increases the clinical importance of accurately measuring high-frequency hearing aid output (Moore, Glasberg, and Stone 2010).

1.1. Integrated pressure level (IPL) measurement and the development of IPL wRECD

In-ear sound-level calibration using Thevenin-equivalent source parameter calibrated stransducers can reliably quantify input to the auditory system up to 16 000 Hz without standing wave interference (Souza et al. 2014; Lapsley Miller et al. 2018). Instead of using a probe-tube microphone placed proximal to the eardrum, Thevenin-equivalent source parameter calibrated transducers measure the sound-level using a microphone flush with the sound source and housed within the same transducer. The calibrated transducer is placed distal from the eardrum in the ear canal. This procedure enables sound-level measurement methodologies that separate the subcomponents of sound (forward-
moving and reflected) to estimate sound levels at the eardrum itself rather than the direct measurement of SPL near the eardrum (Souza et al. 2014). One such measurement is the integrated pressure level (IPL), which is the sum of the in-phase magnitudes of the forward-moving and reflected sound waves (Withnell et al. 2009; Lewis et al. 2009). IPL is theoretically equivalent to the SPL at the termination of a cavity, such as the eardrum (Scheperle, Goodman, and Neely 2011; Lewis et al. 2009; Souza et al. 2014). This equivalence has been validated in artificial cavities with IPL being accurate within 1 dB to directly measured terminal SPL (Lewis et al. 2009). In human ears, IPL results in greater accuracy up to and beyond 8000 Hz compared to SPL-based calibration procedures (Souza et al. 2014). Extending on these findings, an IPL-based foam-tip wRECD procedure has been developed and validated (Urichuk, Purcell, and Scollie 2023). IPL wRECD has significantly improved test-retest reliability compared to SPL wRECD at least up to 8000 Hz (Urichuk, Purcell, and Scollie 2023). In addition, IPL wRECD agreed with SPL wRECD at and below 4000 Hz – the frequency range that SPL wRECD is validated. In this range of frequencies, median differences between IPL wRECD and SPL wRECD are not clinically significant (i.e. $< \pm 3$ dB). Above 4000 Hz, IPL wRECD results in higher wRECD values compared to SPL-based approaches where 3/4-wavelength standing wave error is known to negatively impact SPL wRECD accuracy.

Current clinical probe-microphone wRECD measurements are completed with either a foam-tip coupling, or with the individual's earmold attached to a variable length of hearing aid tubing. The choice of coupling, as well as the choice of the transducer, have been shown to significantly alter wRECD values (Bagatto et al. 2005; Gustafson, Pittman, and Fanning 2013; Moodie, Pietrobon, et al. 2016; Munro and Salisbury 2002; Munro and Toal 2005). These differences are largely due to interaction between impedances of the hearing aid tubing and the transducer, with increased tubing length leading to larger errors in REAR prediction if the effects of tubing length are unknown (Bagatto et al. 2005; Gustafson, Pittman, and Fanning 2013; Moodie, Pietrobon, et al. 2016). Yet, because the use of custom earmolds remains preferred practice for paediatric hearing aid fitting (AAA, 2013), quantification of earmold tubing effects via measurement of an earmold-based "RECD" is one available clinical strategy. As an alternative, an averaged correction between earmold and foam-tip coupling can estimate earmold "RECD" from a measured foam-tip RECD (Moodie, Pietrobon, et al. 2016). This correction has been implemented in at least one hearing aid verification system (Moodie, Pietrobon, et al. 2016). However, it is still recommended to directly measure the RECD using the individual's earmold when possible, to capture individual variability in tubing length (Moodie, Pietrobon, et al. 2016). Although this is straightforward with clinical equipment that uses SPL measurement, it is less feasible to attach individual earmold tubing to an IPL measurement system. One alternative may be to measure the IPL response of an individual's earmold tubing and combine it with an IPL wRECD measure made with a foam tip. This two-stage procedure is conceptually similar to the earmold-to-foam-tip correction described above but could allow IPL measurement of the individual ear canal and hearing aid tubing effects. They would be measured separately, but together estimate an individual earmold wRECD. The equation for this two-stage process is:

$$\textit{predicted earmold IPL wRECD} = \textit{IPL wRECD} + \textit{HA tubing transform} \quad (8)$$

The two-stage predicted earmold IPL wRECD may allow accurate conversion between the individual's wRECD and earmold wRECD independent of the individual's hearing aid tubing length. Therefore, the purposes of the current study are:

1. To validate measurement of the predicted earmold IPL wRECD using a two-stage procedure
2. To compare predicted earmold IPL wRECDs with earmold SPL wRECDs
3. To compare accuracy of the acoustically measured hearing aid tubing length correction to a published average tubing length correction.

We hypothesised that the predicted earmold IPL wRECD would accurately determine earmold SPL wRECD for frequencies below 4000 Hz. Above 4000 Hz, we hypothesised that predicted earmold IPL wRECD would overestimate directly measured earmold SPL wRECD due to ¾-wavelength standing wave errors being present in probe-microphone SPL wRECD measurements. Finally, we expected that an individualised estimation of tubing length would provide a more accurate estimate than an average correction for tubing length.

2. Materials and methods

2.1. Participants

A total of 22 adult participants (4 male; 18 female) between 21 and 30 years of age were recruited from the Western University School of Communication Sciences and Disorders. All participants had normal hearing determined by a basic audiometric screening at 25 dB HL at all octave frequencies between 250 and

	Insert earphone wRECD	Earmold wRECD		
wRECD type	Foam-tip SPL wRECD	Predicted Earmold SPL wRECD	Earmold SPL wRECD	SPL
Microphone	probe-tube microphone	probe-tube microphone	probe-tube microphone	
Measurement location	near eardrum	near eardrum	near eardrum	
Coupling method	generic foam tip	generic foam tip	individual's earmold	
Tubing length correction	none	average tubing length correction (Moodie et al. 2016)	none	
wRECD type	IPL wRECD	Predicted Earmold IPL wRECD		IPL
Microphone	housed in transducer	housed in transducer		
Measurement location	entrance of ear canal	entrance of ear-canal		
Coupling method	generic plastic tip	generic plastic tip		
Tubing length correction	none	acoustically measured tubing length correction (Appendix I)		

Figure 1. Measurement procedure for determining the insert earphone and earmold wRECD using SPL or IPL based wRECD measurement approaches. Each measurement type is referred to in the current study using the underlined term associated with each procedure.

8000 Hz. Normal external and middle ear status was confirmed via otoscopy and type A tympanograms. Western University's Health Sciences Research Ethics Board approval was obtained prior to data collection (REB #116805).

2.2. Procedure

Testing was completed in a quiet laboratory at the National Centre for Audiology at Western University. Probe-microphone wRECD measurements were completed with an Audioscan Verifit 2 using an RE-770 transducer. Measurements were made using a generic foam-tip insert (foam-tip SPL wRECD condition) and an individual's earmold with a variable length of #13 hard wall hearing aid tubing (earmold SPL wRECD condition) in all participants. IPL measurements were completed using an Interacoustics Titan transducer using a modified MATLAB (Mathworks, Natick, MA, United States) script built on the Interacoustics Research Platform. Source parameter calibration was completed weekly.

The same stimulus used and described in Urichuk, Purcell, and Scollie (2023) was used in the current study. A wideband transient click-like stimulus (226–8000 Hz; 21 Hz presentation rate) was presented by an Interacoustics Titan transducer at 96 dB peak-to-peak equivalent SPL (peSPL). The stimulus was calibrated by connecting the Titan transducer to the opening of a Brüel & Kjaer (B + K) type 4157 ear simulator using an ER38-14A foam insert. The transducer was placed and secured with putty such that the opening of the foam tip was attached at the reference measurement plane of the ear simulator, perpendicular to the ear canal axis (Brüel & Kjaer A/S n.d.). The ear simulator was then connected to a B + K type 4192 microphone (Nærum, Denmark) which was then connected to a B + K conditioning amplifier set to 316 milliVolts/Pascal. The amplifier was connected to a USBPre 2 external soundcard (Sound Devices, WI, United States) set to full-scale. Output was sent to SpectraPLUS software (Pioneer Hill Software, WA, United States), where all measurements were referenced to a SpectraPLUS calibration file measuring a 94 dB SPL tone at 1000 Hz produced by a B + K type 4231 calibrator. Source parameter calibration was completed weekly on four waveguides of 12, 14.5, 17.5, and 20 mm using the calibration procedure that accounts for evanescent waves outlined by Nørgaard, Fernandez-Grande, and Laugesen (2017). In-situ IPL measurement used individualised characteristic impedance calculation (Rasetshwane and Neely 2011; as implemented in Urichuk, Purcell, and Scollie 2023).

The testing session consisted of seven total measurements in three conditions randomised across participants: (1) foam-tip SPL wRECD measurement (2 measurements; test-retest); (2) IPL wRECD measurement (2 measurements; test-retest); (3) earmold SPL wRECD measurement in each of three tubing length conditions: short, medium and long. The three tubing length conditions corresponded to the length of tubing that fit an individual's ear anatomy ("medium" condition), ± ∼10 mm ("long" and "short", respectively). Average tubing length was 32.0 mm (SD = 2.48), 39.6 mm (SD = 4.17) and 47.7 mm (SD = 3.06) for short, medium and long tubing length conditions, respectively.

The seven measurements were used to determine four wRECDs (Figure 1): (1) IPL wRECD, (2) predicted earmold IPL wRECD, (3) predicted earmold SPL wRECD and (4) earmold SPL wRECD.

In each SPL condition, the real-ear response was measured using a probe-tube placed into the ear canal within 5 mm of the individual's tympanic membrane, verified using a validated probe-tube insertion guide (Folkeard et al. 2019) and otoscopic visualisation. If probe-tube movement occurred during transducer placement, as observed by the tube position marker, probe-microphone placement was re-completed.

All IPL wRECD measurements were made using a plastic acoustic immittance tip coupled with the source-parameter calibrated transducer. A broadband transient stimulus, described below, was presented to the ear-canal. The pressure response to a broadband transient stimulus presented to the ear-canal was measured by the transducer-housed microphone. For the predicted earmold IPL wRECD, the tubing length was measured acoustically prior to the in-ear measurement. The tubing was coupled to the IPL wRECD transducer using a silicone coupling sleeve with inner diameter of 3.125 mm and an acoustic length measurement was completed (Supplementary Appendix 1). A correction based on the acoustic length was calculated and added to the IPL wRECD measurement to obtain the predicted earmold IPL wRECD (Figure 1). The transducer was fully removed and re-inserted between all measurements.

2.3. Analysis

Analysis of all measurements was completed in 1/3 octave bands between 250 and 8000 Hz. Mixed-effect linear models were constructed to assess the relationships between predictor variables and outcome variables of interest. Participants were coded as random effects across all models. *p* values were obtained using likelihood ratio tests of a model compared against a model without the effect of interest. When necessary, *post-hoc* comparisons of estimated marginal means using Tukey honestly significant difference (HSD) corrections for multiple comparisons were completed. Test-retest reliability was assessed using intraclass correlation coefficients (absolute agreement) and evaluated using a classification system of excellent (ICC >0.9), good (0.9 > ICC > 0.75), moderate (0.75 > ICC > 0.5) or poor (0.5 > ICC; Koo and Li 2016).

Clinically significant differences were determined using averaged mean differences and corresponding estimated 95% confidence intervals for the difference between real-ear measurements and RECDs reported by Munro and Davis (2003). Such a method for determining clinical significance has been used previously to validate the SPL wRECD and IPL wRECD procedure using a cut-off of 3 dB (Vaisberg et al. 2018; Urichuk, Purcell, and Scollie 2023). In the current study, mean differences between predicted earmold IPL wRECD and earmold SPL wRECD measurements that fell within 3 dB were determined to be clinically insignificant.

2.4. Data exclusion

Analysis of all measurements was completed offline. Measurements were excluded when an acoustic leak was present: One earmold wRECD measurement with substantial attenuation of wRECD values in low frequencies was excluded (de Jonge 1996). Two IPL measurements with low-frequency power absorbance magnitude >0.29 and low-frequency admittance phase <44 degrees were also excluded (Groon et al. 2015).

3. Results

3.1. Comparison between earmold IPL wRECD and earmold SPL wRECD

Both predicted earmold IPL wRECD and earmold SPL wRECDs provided values between −20 and +20 dB relative to a 2 cc coupler (Figure 2). Predicted earmold IPL wRECD measurements yielded similar values to the earmold SPL wRECD in the mid-frequency region (Figure 2). In both low and high frequencies, predicted earmold IPL wRECD values were greater than earmold SPL wRECD values. To evaluate whether the predicted earmold IPL wRECD procedure produced values significantly different than earmold SPL wRECD, the differences between the two were assessed as the outcome of a linear mixed model. Frequency and hearing aid tubing length (with interactions) were set as fixed effects with the random intercept of participant. A significant main effect of frequency was observed (χ^2_{15} = 4957, $p < 0.001$), with no significant main effect of hearing aid tubing length (χ^2_1 = 0.10, $p = 0.75$). A significant interaction between hearing aid tubing length and frequency was also observed (χ^2_{15} = 118.47, $p < 0.001$), indicating that statistically significant frequency specific differences between measurement methodologies caused by tubing length were observed.

The differences between predicted earmold IPL wRECD and earmold SPL wRECD were less than 3 dB between 500 and 2500 Hz (Figure 2(B)). At frequencies below 500 Hz, IPL wRECD exceeded probe-microphone wRECD by more than 3 dB with the largest difference of 8 dB observed at 250 Hz. At all frequencies above 2500 Hz, predicted earmold IPL wRECDs exceeded earmold SPL wRECDs by more than 3 dB (Figure 2(B)).

3.2. Validation of individualised hearing tubing length correction

Predicted earmold IPL wRECDs are plotted across earmold tubing lengths wRECDs in Figure 3. Increased length of tubing was associated with a lower-frequency notch in the average wRECD response shape. These predicted earmold IPL wRECDs were compared to earmold SPL wRECDs and to predicted earmold SPL wRECD procedures, which use published averaged tubing length corrections. The average error associated with these strategies are shown in the bottom row of Figure 3. The acoustically measured tubing length correction produced smaller errors associated with tubing length compared to averaged transforms (Figure 3). As seen in the top left panel of Figure 3, there is a systematic effect of hearing aid tubing length on the earmold SPL wRECD. All else being equal, shorter tubing lengths result in smaller earmold SPL wRECD values for frequencies below 2000 Hz when compared to the same measurement completed with a longer segment of tubing. Between 2000 and 4000 Hz, the shorter tubing length has an opposite effect, producing larger earmold SPL wRECD values than are found when longer tubing is used. When average transforms are used to predict earmold SPL wRECD, systematic error caused by tubing length is apparent (Figure 3(E)). In contrast, when individualised tubing length transforms are incorporated into predicted earmold IPL wRECDs, systematic variation caused by tubing length is minimised, indicating that acoustic effects of hearing aid tubing length are being accounted for in the correction (Figure 3(D)).

Maximum anticipated residual errors associated with tubing length are shown in Figure 4 for both average and acoustically measured tubing length corrections. This error is determined by comparing the error associated with 50 mm of tubing compared to the error associated with 30 mm of tubing, equivalent to subtracting the 50 and 30 mm conditions from the bottom panels of Figure 3. Specifically, the predicted earmold IPL wRECD is used for the acoustically measured tubing length correction and predicted earmold SPL wRECD is used for the average tubing length correction. If a correction fully accounted for the acoustic differences caused by changes in tubing length, the difference would be 0 dB. Any frequency where the 95% confidence interval, indicated by error bars, does not encompass 0 dB indicates a statistically significant effect of tubing length on the prediction of the earmold wRECD. The acoustically measured tubing length correction largely minimises the ± 6 dB errors seen above 1000 Hz when it is not measured. However, there is still a significant effect of tubing length on the predicted wRECD most pronounced near 1600 Hz and above 5000 Hz. These results indicate that the individualised tubing length corrections overcorrected at 1600 and 8000 Hz, while under-correcting at 6300 Hz. However, these differences are much smaller than those seen in the average foam-tip-to-earmold corrections and largely do not exceed an error of 3 dB, which was deemed to be clinically significant.

3.3. Test-retest reliability of predicted earmold IPL wRECD measurement

Predicted earmold IPL wRECD was highly reliable in all test subjects, with participants having median differences of less than 1.5 dB across all 1/3 octave bands (Figure 5(A)). Individual test-retest differences fell below the 3 dB clinically significant criterion in 661/668 (98.9%) 1/3 octave bands analysed (43 ears

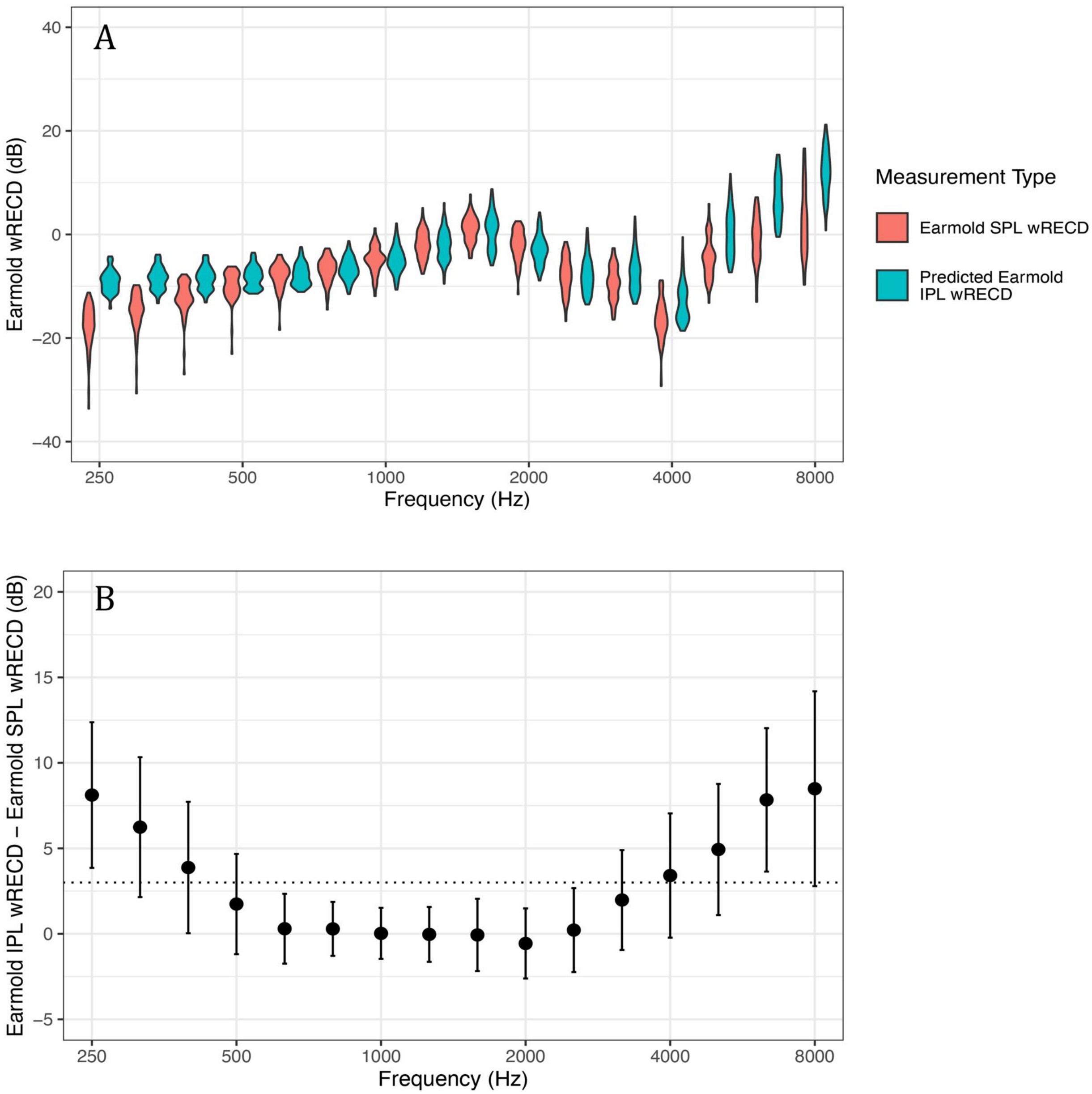

Figure 2. (A) Distribution of all earmold wRECD measurements across all tubing length conditions using both earmold IPL wRECD and SPL wRECD. Each pair of symbols are for the 1/3 octave band indicated on the horizontal axis. Width of distribution indicates density of measurements yielding a specific wRECD for a given 1/3 octave band. (B) Mean and standard deviation of the difference in individual measurements between an individual's predicted earmold IPL wRECD and their earmold SPL wRECD across all hearing aid tubing conditions.

* 16 1/3 octave bands), with only 4 participants having any 1/3 octave bands exceeding 3 dB test-retest differences. In comparison, intrasession test-retest reliability of wRECD measurement using re-analysis of data collected by Vaisberg et al. (2018) found that absolute test-retest differences exceeded 3 dB in more than 25% of all measurements at 250, 6300, and 8000 Hz. ICC values for each 1/3 octave band for each method of earmold wRECD are reported in Table 1. Predicted earmold IPL wRECD was found to be more reliable than earmold SPL wRECD measurement across the entire frequency range. At frequencies of 4000 Hz or greater, predicted earmold IPL wRECD reliability was good-to-excellent while earmold SPL wRECD values produced moderate-to-good reliability. In the mid-frequencies between 1000 and 4000 Hz, predicted earmold IPL wRECD had excellent reliability whereas earmold SPL wRECD yielded good reliability. Finally, low-frequency reliability in predicted earmold IPL wRECD was found to be good, whereas earmold SPL wRECD reliability was found to be moderate, likely due to the presence of slit leakage, potentially caused by theprobe-microphone. The current results suggest that predicted earmold IPL wRECD is a valid and reliable alternative to earmold SPL wRECD measurement.

4. Discussion

4.1. Main findings

Similar to comparisons with foam-tip SPL wRECD determination, predicted earmold IPL wRECD measurements produced larger high-frequency values than earmold SPL wRECD measurements. Such a deviation was anticipated, due to the effects of standing wave error in the SPL measurements. Predicted earmold IPL wRECD fell within 3 dB of the earmold SPL wRECD for all frequencies between 500 and 2500 Hz regardless of the earmold's

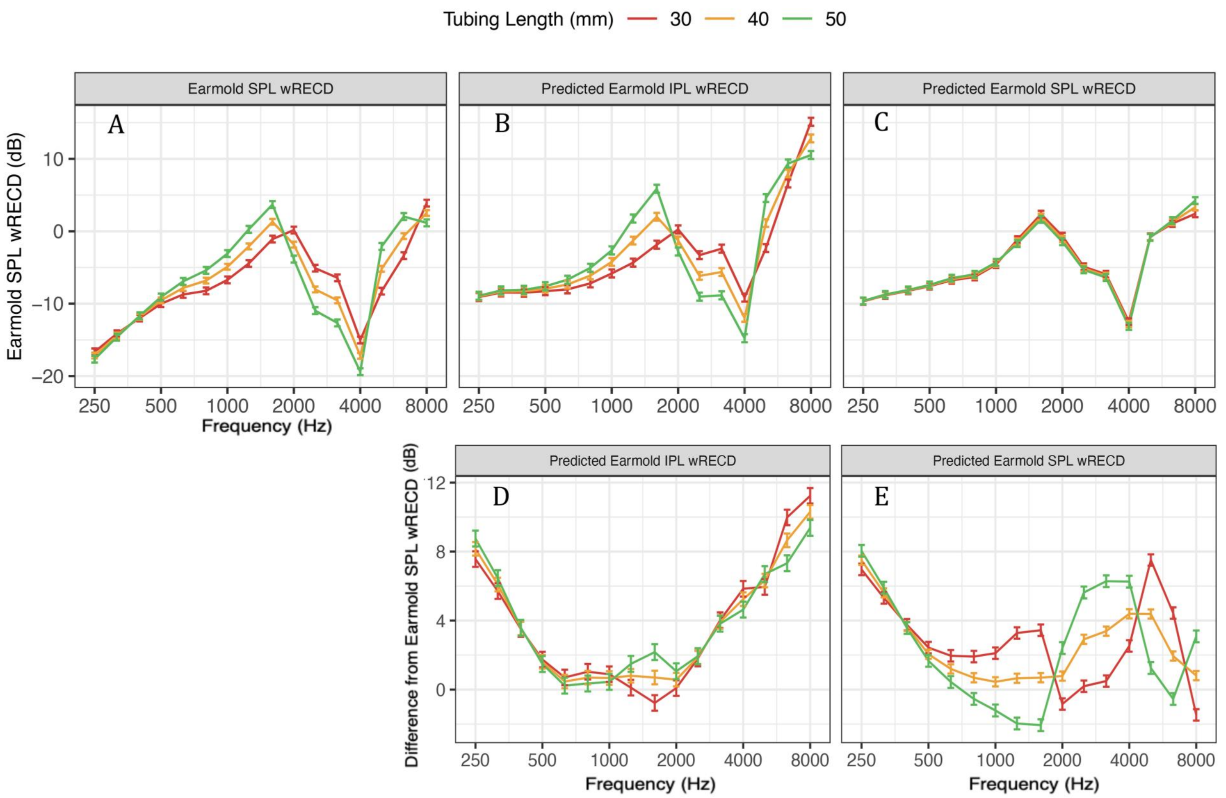

Figure 3. (Top row) earmold wRECD average values in the linear mixed model for earmolds attached to 30, 40, and 50 mm of hearing aid tubing using earmold SPL wRECD data (A), predicted earmold IPL wRECD (B) and predicted earmold SPL wRECD (C). Error bars indicate ± 1 standard error. (Bottom row) Difference between earmold SPL wRECD and the predicted earmold IPL wRECD (D) or predicted earmold SPL wRECD (E). Positive values indicate larger estimated wRECD values than measured by probe-tube.

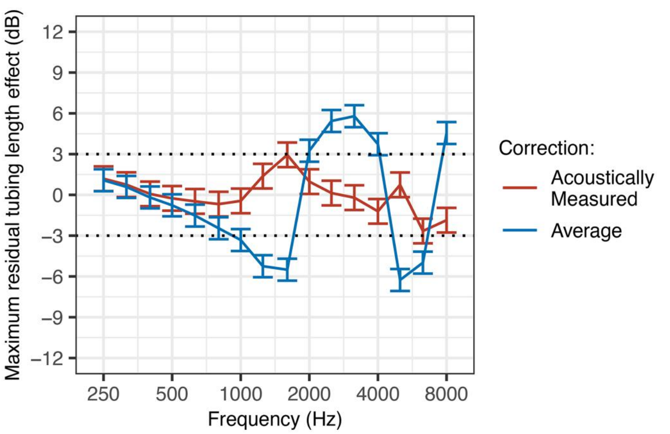

Figure 4. Difference in earmold wRECD estimate error between two extreme tubing lengths (average 50 mm earmold wRECD minus average 30 mm earmold wRECD) using two tubing length correction methods. Y-axis indicates the direction and maximum magnitude of systematic error caused by increasing tubing length for each tubing length correction methodology. The magnitude of the residual tubing length error following the correction, either acoustically measured (black) or average (grey) are shown. Deviations from zero indicate statistically significant effects caused by hearing aid tubing length differences. Clinically significant cut-offs are shown by the dotted lines falling at ±3 dB. Error bars indicate 95% confidence interval for each estimate (2*SE).

tubing length. At frequencies below 500 Hz, both predicted earmold IPL wRECD and predicted earmold SPL wRECD produced larger values than the directly measured earmold SPL wRECD due to probe-tube-induced slit leak error being present in the earmold SPL wRECD measurement. Unexpectedly, differences between the earmold SPL wRECD and predicted earmold SPL wRECD were observed near 4000 Hz. This systematic deviation was independent of the tubing length, indicating potential systematic differences in acoustic responses between coupling methods unrelated to the tubing length.

The test-retest reliability of predicted earmold IPL wRECD exceeded the reliability of earmold SPL wRECD measurements across all analysed frequencies. Predicted earmold IPL wRECD test-retest reliability was assessed to be excellent, with almost all test-retest errors falling below a clinically significant criterion of 3 dB across all analysed 1/3 octave bands. Reliability improvements were especially marked in the low frequencies and above 4000 Hz, due to reduced slit leak error and reduced standing-wave error, respectively. The current results support the use of predicted earmold IPL wRECD measurements in an adult population. These results, in addition to the validation of foam-tip IPL wRECD measurement in a companion study (Urichuk, Purcell, and Scollie 2023), indicate that it may be possible and beneficial to replace probe-microphone wRECD measurements with IPL wRECD measures to improve accuracy. Predicted earmold IPL wRECD improves test-retest reliability and does not significantly change wRECD determination between 500 and 2500 Hz and agrees well with earmold SPL wRECDs. It is expected that the predicted earmold IPL wRECD will result in improved high-frequency accuracy. Further evaluation of this measurement in children is indicated.

4.2. Comparison between earmold IPL and SPL wRECD

The current results suggest that measurement of a predicted earmold IPL wRECD accounts for individual variation in tubing

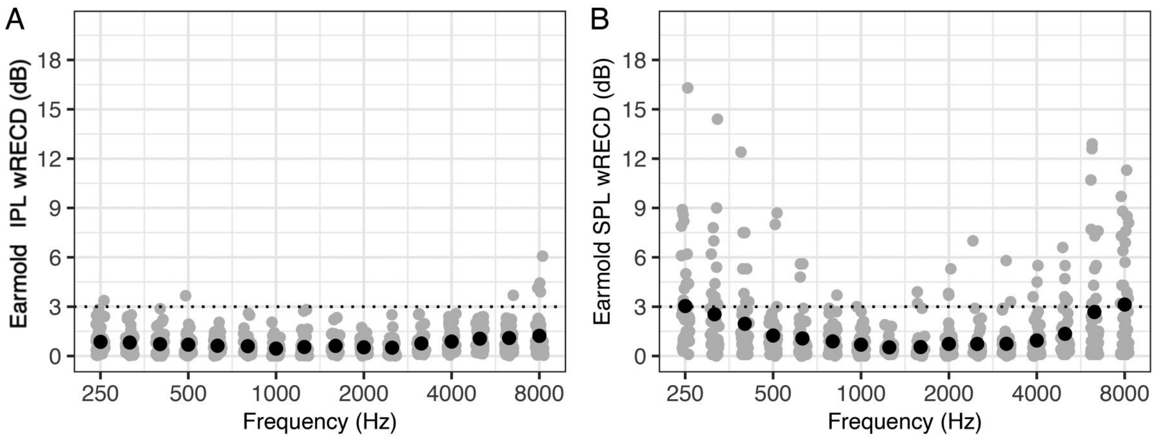

Figure 5. Absolute test-retest differences in dB for (A) Earmold IPL wRECD for 22 individuals in the current study (B) Test-retest data of 22 individuals, re-analysed from Vaisberg et al. (2018) using each individual's personal earmold.

Table 1. Intraclass correlation values of absolute agreement for test-retest reliability.

Frequency (Hz)	Earmold IPL wRECD	Earmold SPL wRECD
250	**0.84** [0.72–0.91]	**0.64** [0.42–0.79]
500	**0.88** [0.79–0.94]	**0.74** [0.57–0.85]
1,000	**0.96** [0.93–0.98]	**0.86** [0.76–0.92]
2,000	**0.95** [0.90–0.97]	**0.89** [0.81–0.94]
2,500	**0.96** [0.92–0.98]	**0.82** [0.69–0.90]
3,150	**0.94** [0.90–0.97]	**0.76** [0.60–0.87]
4,000	**0.93** [0.88–0.96]	**0.72** [0.53–0.84]
5,000	**0.93** [0.87–0.96]	**0.84** [0.73–0.91]
6,300	**0.93** [0.88–0.96]	**0.55** [0.30–0.73]
8,000	**0.89** [0.80–0.94]	**0.70** [0.51–0.83]

Intraclass correlation coefficients of absolute agreement (bold) and the corresponding 95% confidence intervals in brackets. Earmold SPL wRECD Intraclass correlation coefficient (ICC) values were determined using reanalysed data originally published in Vaisberg et al. (2018).

length and yields earmold wRECD values within 3 dB of earmold SPL wRECD between 500 and 2500 Hz (Figure 3(E)). As a result, the predicted earmold IPL wRECD is a more accurate alternative to estimating the earmold wRECD compared to using a foam-tip wRECD with an average foam-tip-to-earmold transform (Figure 3(D)). Results between earmold SPL wRECD and the predicted earmold IPL wRECD differed in in both the low- (<=500 Hz) and high- (>=4000 Hz) frequency regions, due to slit leak and standing-wave interference, respectively.

Slit leak errors in earmold SPL wRECD can be caused by probe-tube-induced gaps between the ear canal wall and earmold that are not present when the individual is wearing the hearing aid outside of this verification measurement (Mueller 2001). The two-step calculation of the predicted earmold IPL wRECD avoids slit leak errors caused by gaps between the probe-microphone and ear-mold by eliminating probe-microphone placement altogether. Slit leak errors are further minimised by robust leak-detection criteria resulting from the simultaneous wideband acoustic immittance measurement adapted for use in the current study (Groon et al. 2015). This is believed to be a significant reason for the larger low-frequency predicted earmold IPL wRECD values compared to earmold SPL wRECDs. Likewise, the larger values obtained in the high-frequencies for predicted earmold IPL wRECD relative to the probe-microphone approach are thought to be caused by the known presence of standing-wave error in any probe-microphone measured wRECD. The likelihood of this explanation is strengthened further by the consistency of the shape and magnitude of the differences between IPL wRECD and probe-microphone measured SPL wRECD regardless of coupling method (foam-tip or earmold).

4.3. Validation of individualised tubing length corrections

The acoustic response of each individual tubing length was estimated using the source parameter calibrated transducer with methods described in Supplementary Appendix I. These methods predicted the earmold IPL wRECD using two measurements. In the first measurement, the IPL wRECD (with generic insert) is measured in the ear. In the second stage, the length of the tubing is acoustically determined using the response of the earmold tubing measured on the desk, which takes seconds to complete. The length of the hearing aid tubing is used to create a tubing length correction for that particular hearing aid user, which is added to the IPL wRECD values to produce the predicted earmold IPL wRECD. This is similar in concept to the foam-tip-to-earmold transform developed by Moodie, Pietrobon, et al. (2016), which used the average acoustic effect of hearing aid tubing between 30 and 50 mm in length. However, this approach builds upon that of Moodie, Pietrobon, et al. (2016) by acoustically determining the length of the individual's tubing, to determine the impact of the tubing length more accurately. The proposed acoustically measured tubing length correction largely eliminates the error in earmold wRECD prediction caused by variation in tubing length that has been observed in previous studies (Munro and Davis 2003; Gustafson, Pittman, and Fanning 2013; Moodie, Pietrobon, et al. 2016) as well as in this study (Figure 3(A)). Although it would be theoretically possible to physically measure the individual's tubing with a ruler, a significant portion of the tubing is embedded within the earmold itself and not solely a straight line. As a result, doing so would be cumbersome and error prone to try to do in a clinical setting.

Differences independent of tubing-length were observed between predicted earmold IPL wRECD and earmold SPL wRECD. If the tubing length was the only cause of differences, we would expect to see no differences between the two measures, however, a clear, clinically meaningful, increase in earmold wRECD is observed in the low (<500 Hz) and high (>3150 Hz) frequency regions as discussed previously. The consistent over-estimation between predicted earmold IPL wRECD and earmold SPL wRECD requires further investigation. Nonetheless, incorporation of the individualised tubing correction minimised ±6 dB variations in predicted earmold IPL wRECD caused by tubing length differences.

5. Conclusion

Predicted earmold IPL wRECD yield clinically similar values as earmold SPL wRECD measurements within 500–2500 Hz without requiring the placement of a probe-microphone. Predicted earmold IPL wRECD are more reliable and easier to complete compared to probe-microphone measurements and provide a simultaneous middle ear assessment using wideband acoustic immittance. The effect of hearing aid tubing on the earmold wRECD can be accounted for using a brief, out-of-ear measurement of the earmold using the same device. The speed of the measurement and extended bandwidth of IPL wRECD measurements are likely to improve hearing instrument workflows.

Acknowlegements

The authors are grateful to Bernafon Canada for providing all earmolds used in the current study and to Jonathan Vaisberg for sharing raw data from previous studies. The authors are also grateful to Audioscan, a Division of Etymotic Design Incorporated, and Interacoustics A/S for their technical support throughout the study.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Ontario Research Fund [RE-08-072].

References

Alexander, J. M., and V. Rallapalli. 2017. “Acoustic and Perceptual Effects of Amplitude and Frequency Compression on High-Frequency Speech.” *The Journal of the Acoustical Society of America* 142 (2):908–923. https://doi.org/10.1121/1.4997938

American Academy of Audiology (AAA). 2013. *Clinical Practice Guidelines Pediatric Amplification*. Accessed October 15, 2020. https://www.audiology.org/wpcontent/uploads/legacy/publications/PediatricAmplificationGuidelines.pdf

American National Standards Institute (ANSI). 2013. *Methods of Measurement of Real-Ear Performance Characteristics of Hearing Aids. ANSI S3.46-2013*. New York, NY: Acoustical Society of America.

Brüel & Kjaer A/S. (n.d.). “Technical Documentation: Ear Simulator Type 4157.” BE 0629–13.

Bagatto, M., S. Moodie, S. Scollie, R. Seewald, S. Moodie, J. Pumford, and K. P. R. Liu. 2005. “Clinical Protocols for Hearing Instrument Fitting in the Desired Sensation Level Method.” *Trends in Amplification* 9 (4):199–226. https://doi.org/10.1177/108471380500900404

Brennan, M. A., R. McCreery, J. Kopun, B. Hoover, J. Alexander, D. Lewis, and P. G. Stelmachowicz. 2014. “Paired Comparisons of Nonlinear Frequency Compression, Extended Bandwidth, and Restricted Bandwidth Hearing Aid Processing for Children and Adults with Hearing Loss.” *Journal of the American Academy of Audiology* 25 (10):983–998. https://doi.org/10.3766/jaaa.25.10.7

Chan, J. C. K., and C. D. Geisler. 1990. “Estimation of Eardrum Acoustic Pressure and of Ear Canal Length from Remote Points in the Canal.” *The Journal of the Acoustical Society of America* 87 (3):1237–1247. https://doi.org/10.1121/1.398799

de Jonge, R. 1996. “Real-Ear Measures: Individual Variation and Measurement Error.” In *Hearing Aids: Standards, Options, and Limitations*, edited by M. Valente, 72–125. New York: Thieme Medical Publishers.

Feigin, J. A., J. Kopun, P. Stelmachowicz, and M. Gorga. 1989. “Probe-Tube Microphone Measures of Ear-Canal Sound Pressure Levels in Infants and Children.” *Ear and Hearing* 10 (4):254–258. https://doi.org/10.1097/00003446-198908000-00008

Folkeard, P., J. Pumford, J. Pietrobon, and S. Scollie. 2019. “Evaluation of Probe Guide: Software-Assisted Probe Tube Placement in Hearing Aid Fittings.” *Hearing Review* 26 (11).

Folkeard, P., M. Van Eeckhoutte, S. Levy, D. Dundas, P. Abbasalipour, D. Glista, S. Agrawal, and S. Scollie. 2021. “Detection, Speech Recognition, Loudness, and Preference Outcomes with a Direct Drive Hearing Aid: Effects of Bandwidth.” *Trends in Hearing* 25:2331216521999139. https://doi.org/10.1177/2331216521999139

Füllgrabe, C., T. Baer, M. A. Stone, and B. C. J. Moore. 2010. “Preliminary Evaluation of a Method for Fitting Hearing Aids with Extended Bandwidth.” *International Journal of Audiology* 49 (10):741–753. https://doi.org/10.3109/14992027.2010.495084

Groon, K. A., D. M. Rasetshwane, J. G. Kopun, M. P. Gorga, and S. T. Neely. 2015. “Air-Leak Effects on Ear-Canal Acoustic Absorbance.” *Ear and Hearing* 36 (1):155–163. https://doi.org/10.1097/AUD.0000000000000077

Gustafson, S., A. Pittman, and R. Fanning. 2013. “Effects of Tubing Length and Coupling Method on Hearing Threshold and Real-Ear to Coupler Difference Measures.” *American Journal of Audiology* 22 (1):190–199. https://doi.org/10.1044/1059-0889(2012/12-0046)

Hornsby, B. W. Y., E. E. Johnson, and E. Picou. 2011. “Effects of Degree and Configuration of Hearing Loss on the Contribution of High- and Low-Frequency Speech Information to Bilateral Speech Understanding.” *Ear and Hearing* 32 (5):543–555. https://doi.org/10.1097/AUD.0b013e31820e5028

International Electrotechnical Commission (IEC). 2016. “Electroacoustics – Hearing aids – Method for measuring electroacoustic performance up to 16 kHz.” *IEC TS* 62886:2016.

Koo, T. K., and M. Y. Li. 2016. “A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research.” *Journal of Chiropractic Medicine* 15 (2):155–163. https://doi.org/10.1016/j.jcm.2016.02.012.

Lapsley Miller, J. A., C. M. Reed, S. R. Robinson, and Z. D. Perez. 2018. “Pure-Tone Audiometry With Forward Pressure Level Calibration Leads to Clinically-Relevant Improvements in Test–Retest Reliability.” *Ear and Hearing* 39 (5):946–957. https://doi.org/10.1097/AUD.0000000000000555

Levy, S. C., D. J. Freed, M. Nilsson, B. C. J. Moore, and S. Puria. 2015. “Extended High-Frequency Bandwidth Improves Speech Reception in the Presence of Spatially Separated Masking Speech.” *Ear and Hearing* 36 (5): e214–e224. https://doi.org/10.1097/AUD.0000000000000161

Lewis, J. D., R. W. McCreery, S. T. Neely, and P. G. Stelmachowicz. 2009. “Comparison of *In-Situ* Calibration Methods for Quantifying Input to the Middle Ear.” *The Journal of the Acoustical Society of America* 126 (6): 3114–3124. https://doi.org/10.1121/1.3243310

McCreery, R. W., A. Pittman, J. Lewis, S. T. Neely, and P. G. Stelmachowicz. 2009. “Use of Forward Pressure Level to Minimize the Influence of Acoustic Standing Waves during Probe-Microphone Hearing-Aid Verification.” *The Journal of the Acoustical Society of America* 126 (1):15–24. https://doi.org/10.1121/1.3143142

McCreery, R. W., E. A. Walker, M. Spratford, R. Bentler, L. Holte, P. Roush, J. Oleson, J. Van Buren, and M. P. Moeller. 2015. “Longitudinal Predictors of Aided Speech Audibility in Infants and Children.” *Ear and Hearing* 36 (Suppl 1):24S–37S. https://doi.org/10.1097/AUD.0000000000000211

Moodie, S., R. C. Seewald, and S. Sinclair. 1994. “Procedure for Predicting Real-Ear Hearing Aid Performance in Young Children.” *American Journal of Audiology* 3 (1):23–31. https://doi.org/10.1044/1059-0889.0301.23

Moodie, S., J. Pietrobon, E. Rall, G. Lindley, L. Eiten, D. Gordey, L. Davidson, K. S. Moodie, M. Bagatto, M. M. Haluschak, et al. 2016. “Using the Real-Ear-to-Coupler Difference within the American Academy of Audiology Pediatric Amplification Guideline: Protocols for Applying and Predicting Earmold RECDs.” *Journal of the American Academy of Audiology* 27 (3):264–275. https://doi.org/10.3766/jaaa.15086

Moore, B. C. J., B. R. Glasberg, and M. A. Stone. 2010. “Development of a New Method for Deriving Initial Fittings for Hearing Aids with Multi-Channel Compression: CAMEQ2-HF.” *International Journal of Audiology* 49 (3):216–227. https://doi.org/10.3109/14992020903296746

Moore, B. C. J., M. A. Stone, and J. I. Alcantara. 2001. “Comparison of the Electroacoustic Characteristics of Five Hearing Aids.” *British Journal of Audiology* 35 (5):307–325. https://doi.org/10.1080/00305364.2001.11745249

Moore, B. C. J., M. A. Stone, C. Füllgrabe, B. R. Glasberg, and S. Puria. 2008. “Spectro-Temporal Characteristics of Speech at High Frequencies, and the Potential for Restoration of Audibility to People with Mild-to-Moderate Hearing Loss.” *Ear and Hearing* 29 (6):907–922. https://doi.org/10.1097/AUD.0b013e31818246f6

Mueller, H. G., and J. W. Hall. 1998. *Audiologists’ Desk Reference*. San Diego: Singular Publishing Group.

Mueller, H. G. 2001. “Probe Microphone Measurements: 20 Years of Progress.” *Trends in Amplification* 5 (2):35–68. https://doi.org/10.1177/108471380100500202

Munro, K. J., and J. Davis. 2003. “Deriving the Real-Ear SPL of Audiometric Data Using the ‘Coupler to Dial Difference’ and the ‘Real Ear to Coupler Difference.” *Ear and Hearing* 24 (2):100–110. https://doi.org/10.1097/01.AUD.0000058114.20741.4D

Munro, K. J., and N. Hatton. 2000. “Customized Acoustic Transform Functions and Their Accuracy at Predicting Real-Ear Hearing Aid Performance.” *Ear and Hearing* 21 (1):59–69. https://doi.org/10.1097/00003446-200002000-00009

Munro, K. J., and V. Salisbury. 2002. “Is the Real-Ear to Coupler Difference Independent of the Measurement Earphone.” *International Journal of Audiology* 41 (7):408–413. https://doi.org/10.3109/14992020209090418

Munro, K. J., and S. Toal. 2005. “Measuring the Real-Ear to Coupler Difference Transfer Function with an Insert Earphone and a Hearing Instrument: Are They the Same? *Ear and Hearing* 26 (1):8.

Nørgaard, K. R., E. Fernandez-Grande, and S. Laugesen. 2017. “Incorporating Evanescent Modes and Flow Losses into Reference Impedances in Acoustic Thévenin Calibration.” *The Journal of the Acoustical Society of America* 142 (5):3013–3024. https://doi.org/10.1121/1.5010891

Rasetshwane, D. M., and S. T. Neely. 2011. “Inverse Solution of Ear-Canal Area Function from Reflectance.” *The Journal of the Acoustical Society of America* 130 (6):3873–3881. https://doi.org/10.1121/1.3654019

Ricketts, T. A., A. B. Dittberner, and E. E. Johnson. 2008. “High-Frequency Amplification and Sound Quality in Listeners with Normal Through Moderate Hearing Loss.” *Journal of Speech, Language, and Hearing Research* 51 (1):160–172. https://doi.org/10.1044/1092-4388(2008/012)

Saunders, G. H., and D. E. Morgan. 2003. “Impact on hearing aid targets of measuring thresholds in dB HL versus dB SPL: El impacto en la medición de los umbrales en dB HL o en dB SPL, en las metas de un auxiliar auditivo.” *International Journal of Audiology* 42 (6):319–326. https://doi.org/10.3109/14992020309101324

Scheperle, R. A., S. S. Goodman, and S. T. Neely. 2011. “Further assessment of forward pressure level for in situ calibration.” *The Journal of the Acoustical Society of America* 130 (6):3882–3892. https://doi.org/10.1121/1.3655878

Scollie, S., R. Seewald, L. Cornelisse, and L. Jenstad. 1998. “Validity and Repeatability of Level-Independent HL to SPL Transforms.” *Ear and Hearing* 19 (5):407–413. https://doi.org/10.1097/00003446-199810000-00007

Seewald, R. C., L. E. Cornelisse, F. M. Richert, and M. G. Block. 1997. “Acoustic Transforms for Fitting CIC Hearing Instruments.” In *CIC Handbook*, edited by M. Chasin, 83–100. San Diego: Singular Publishing Group.

Souza, N. N., S. Dhar, S. T. Neely, and J. H. Siegel. 2014. “Comparison of Nine Methods to Estimate Ear-Canal Stimulus Levels.” *The Journal of the Acoustical Society of America* 136 (4):1768–1787. https://doi.org/10.1121/1.4894787

Tharpe, A. M., D. Sladen, H. M. Huta, and A. M. Rothpletz. 2001. “Practical Considerations of Real-Ear-to-Coupler Difference Measures in Infants.” *American Journal of Audiology* 10 (1):41–49. https://doi.org/10.1044/1059-0889(2000/006)

Urichuk, M., D. Purcell, and S. Scollie. 2023. “Validity and Reliability of Integrated Pressure Level Real-Ear-to-Coupler Difference measurements.” *International Journal of Audiology* :1–10. https://doi.org/10.1080/14992027.2023.2205009

Vaisberg, J. M., S. Beaulac, D. Glista, E. Macpherson, and S. Scollie. 2021. “Perceived Sound Quality Dimensions Influencing Frequency-Gain Shaping Preferences for Hearing Aid-Amplified Speech and Music.” *Trends in Hearing* 25:2331216521989900. https://doi.org/10.1177/2331216521989900

Vaisberg, J. M., P. Folkeard, S. Levy, D. Dundas, S. Agrawal, and S. Scollie. 2021b. “Sound Quality Ratings of Amplified Speech and Music Using a Direct Drive Hearing Aid: Effects of Bandwidth.” *Otology & Neurotology* 42 (2):227–234. https://doi.org/10.1097/MAO.0000000000002915

Vaisberg, J. M., P. Folkeard, J. Pumford, P. Narten, and S. Scollie. 2018. “Evaluation of the Repeatability and Accuracy of the Wideband Real-Ear-to-Coupler Difference.” *Journal of the American Academy of Audiology* 29 (6):520–532. https://doi.org/10.3766/jaaa.17007

Valente, M., H. Abrams, and D. Benson, et al. 2006. "Guidelines for the Audiologic Management of Adult Hearing Impairment. *Audiology Today* 18 (5):1–44.

Valente, M., L. G. Potts, M. Valente, W. Vass, and J. Goebel. 1994. “Intersubject Variability of Real-Ear Sound Pressure Level: Conventional and Insert Earphones.” *Journal of the American Academy of Audiology* 5 (6):9.

Van Eeckhoutte, M., P. Folkeard, D. Glista, and S. Scollie. 2020. “Speech Recognition, Loudness, and Preference with Extended Bandwidth Hearing Aids for Adult Hearing Aid Users.” *International Journal of Audiology* 59 (10):780–791. https://doi.org/10.1080/14992027.2020.1750718

Watts, K. M., M. Bagatto, S. Clark-Lewis, S. Henderson, S. Scollie, and J. Blumsack. 2020. “Relationship of Head Circumference and Age in the Prediction of the Real-Ear-to-Coupler Difference (RECD).” *Journal of the American Academy of Audiology* 31 (7):496–505. https://doi.org/10.3766/jaaa19017

Withnell, R. H., P. S. Jeng, K. Waldvogel, K. Morgenstein, and J. B. Allen. 2009. “An *in situ* Calibration for Hearing Thresholds.” *The Journal of the Acoustical Society of America* 125 (3):1605–1611. https://doi.org/10.1121/1.3075551