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Predicting children's real-ear-to-coupler differences based on tympanometric data

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Abstract

Objective

Pediatric hearing-aid verification relies on measures of output obtained from the ear canal or in a coupler with the child's real-ear-to-coupler difference (RECD). Measured RECD cannot always be completed in children, leading to fitting inaccuracies. Audiologists often have tympanometry data that characterizes the child's ear-canal acoustics. The goal of this study was to determine if tympanometry can be used to improve predictions of measured RECD.

Design

A retrospective analysis of RECD and admittance, tympanometric peak pressure, and equivalent ear-canal volume from 226 Hz tympanometry collected as part of a longitudinal study of children with hearing loss were modelled with Bayesian hierarchical regression.

Study Sample

Two-hundred sixty-six children with mild-to-severe hearing loss contributed data.

Results

Age-based average RECD models were within 3 dB of measured RECD values in 54% of cases with normal middle ear status and 50.6% of cases with abnormal middle ear status. Immittance-predicted RECD were within 3 dB in 69.6% of cases with normal middle ear status and 74.4% of cases with abnormal middle ear status.

Conclusion

Immittance-predicted RECD was more accurate than age-based average RECD, particularly in children with abnormal middle ear status. The findings suggest that 226 Hz tympanometry could be used clinically to improve predictions of measured RECD when it cannot be measured.

Keywords: pediatric, hearing aid, acoustics, real-ear-to-coupler difference, verification, hearing loss

Introduction

Over the last two decades, the average age of identification of hearing loss has been reduced from over 2 years of age (e.g. Moeller, 2000) to under 6 months (Ching et al. 2013; Holte et al. 2012; Wood, Sutton, & Davis, 2015), allowing a greater number of children with hearing loss to receive hearing aids within the first few months of life. This progress necessitated the development of objective hearing-aid verification methods to ensure that speech is audible and that the sound levels produced by the hearing aids are safe (Bagatto et al. 2016). Direct measurement of the hearing-aid output in the ear canal with a probe microphone, known as real-ear or *in situ* verification, is the gold-standard approach for measuring hearing-aid output. *In situ* verification is difficult to complete with infants and young children because it requires head control, cooperation, and multiple measurements in each ear (Bagatto et al. 2005). As an alternative to *in situ* hearing-aid verification, a single measurement of the child's ear canal acoustics, known as the real-ear-to-coupler difference (RECD; Bagatto et al. 2002), can be applied to hearing-aid measurements in a coupler to accurately simulate the output of the hearing aid in the child's ear canal. Despite requiring only a single measurement, however, the RECD still may be difficult to measure due to limited cooperation or middle ear problems. The goal of this study was to examine the application of clinical immittance measures to improve predictions of the RECD when it cannot be easily measured.

Hearing-aid verification with real-ear-to-coupler difference (RECD)

The primary goal of fitting hearing aids for children with hearing loss is to ensure access to the acoustic cues that are needed to promote speech and language development (Joint Committee on Infant Hearing, 2019). Quantifying speech audibility through a hearing aid for infants and young children is challenging because individual variability in ear canal acoustics can have a substantial influence on the output characteristics of hearing aids, even among children who are the same age (Bagatto et al, 2002). For infants and young children, variability in ear canal acoustics is dynamic over time due to changes in ear canal volume, length, and mechanical properties (e.g., ear canal wall compliance; Keefe & Levi, 1996; Keefe et al., 1993). Growth leads to variability in hearing aid output as children get older. Hearing-aid verification measurements using probe microphones were developed to help characterize these sources of variability across individuals and over time (see Mueller, 2001 for review). A flexible, probe microphone tube is placed in the ear canal, the hearing aid is inserted, and the probe-microphone system measures the output of the hearing aid in the ear canal in reference to a sound presented via a loudspeaker in front of the listener. The output of the hearing aid is compared to hearing thresholds converted to dB SPL to estimate the audibility of the amplified speech signal and compare the output to prescriptive targets (Bagatto et al. 2005).

In situ probe-microphone measures are often not possible due to child cooperation or other factors (Moodie et al. 2016). As an alternative to *in situ* probe-microphone verification, the RECD is a single measurement of a child's ear-canal acoustics that can be applied to hearing-aid measurements in a coupler (Moodie, Seewald, & Sinclair, 1994; Sinclair et al. 1996). A measurement of broadband noise is taken in the coupler used for hearing aid verification in a test box. The same signal is delivered to the child's occluded ear canal via their hearing-aid earmold or an insert earphone foam tip. The difference in dB between the measurement in the child's ear canal and the coupler is the RECD. The RECD is applied to hearing-aid measurements in a coupler to simulate the *in situ* hearing-aid output. Smaller ear canals produce larger RECD values, and the RECD decreases as children's ear canals grow and approximate adult size and length. The use of the RECD for simulated hearing-aid verification has been validated in multiple studies involving thousands of children (Bagatto et al. 2002; Bagatto et al. 2005; McCreery et al. 2015) and more recently has been adapted to improve accuracy at high frequencies as the wideband RECD (Vaisberg et al. 2018).

Even though the RECD is a practical alternative when *in situ* hearing-aid verification cannot be completed and only needs to be measured in one ear in most children (Munro & Butterfield, 2005), there are still barriers to measuring individual RECD. A survey of hearing-aid verification practices for pediatric audiologists reported by Moodie and colleagues (2016) found that just under half of audiologists used *in situ* hearing-aid verification often or always with young children, and only around 60% of audiologists reported measuring each child's individual RECD at the time of hearing aid verification. The most common reason reported in the survey for not measuring *in situ* verification or RECD was lack of cooperation from the child during probe-microphone measurements. An earlier study of children fitted with hearing aids found that audiologists used an age-based average RECD instead of the child's individually measured RECD in over 40% of fittings and that fittings based on average RECD had greater deviations from prescriptive targets than fittings where the RECD was individually measured (McCreery et al. 2015). The range of measured RECD around the average RECD is approximately +/- 10-15 dB (Bagatto et al. 2002; McCreery et al. 2015). This variability can lead to inaccuracies in hearing aid fitting of that magnitude when the average RECD is used. Recent studies have attempted to use proxy measures of ear-canal size, such as head circumference (Blumsack et al. 2014; Watts et al. 2020), but these efforts have yielded similar accuracy for predicting RECD as using the child's age. Although the RECD is a valuable alternative to in situ hearing aid verification for children, there are barriers, including child cooperation, that can limit its use.

Improving predictions of RECD using immittance measures

Individual differences in RECD among children and over time occur due to variation in acoustic impedance of the ear canal across listeners. Differences in ear-canal volume and outer- and middle-ear impedance influence the sound pressure level measured in the occluded ear canal. Voss and colleagues (2000b) developed acoustic models to demonstrate that variation in ear-canal sound pressure levels were associated with differences in impedance related to larger residual ear-canal volume that occurs with circumaural headphones compared to insert earphones. Higher impedance resulting from smaller residual ear-canal volume led to higher sound pressure levels than the lower impedance coupling from circumaural headphones with differences as large as 35 dB across earphone types for the same listener (Voss et al. 2000a). These studies demonstrated the potential impact of individual differences in impedance on variability in audiometric assessment across earphones but did not directly assess how differences in impedance influence individual RECD values.

Few studies have examined the potential to predict individual differences in RECD based on individual impedance characteristics. Impedance differences across individual ear canals measured with insert earphones are consistent with differences in ear-canal sound pressure levels observed in studies of age-related changes in the RECD as the ear canal grows (e.g., Bagatto et al. 2005) and adult-child differences in pressure levels between circumaural and insert earphones (Voss et al. 2005). Consistent with previous work by Voss and colleagues (2000a; 2000b), the RECD is larger in ears with middle-ear effusion where impedance is higher (Martin, Westwood, & Bamford, 1996), but smaller at low frequencies in ears with pressure equalization tubes (Martin, Munro, & Langer, 1997) or tympanic membrane perforations (Martin, Munro, & Lam, 2001) when impedance is reduced by the increased volume of the middle-ear cavity. The impedance of the transducer used to measure the RECD, the child's ear canal, and the coupler can all influence the measurement of the RECD (Munro & Toal, 2005). Characterizing individual differences in ear-canal impedance by measuring the sound level in the ear canal using forward pressure level (FPL) improves the accuracy of *in situ* hearing-aid verification (McCreery et al. 2009), but FPL approaches have not been extended to the RECD, primarily because calculating dB SPL currently requires a time-consuming calibration procedure that is not feasible when the RECD cannot be directly measured.

In contrast, individual measures of the impedance of the ear canal and middle ear often are available in young children from tympanometry. Tympanometry is a pressurized measure of middle-ear function that uses a probe tone to estimate the amount of sound that is absorbed by the middle ear (Hunter & Margolis, 1992). The most common approach to tympanometry uses a 226 Hz probe tone to assess the function of the middle ear at low frequencies and has reasonable sensitivity for detecting fluid in the middle-ear space (Shanks & Shelton, 1991). Tympanometry also provides an estimate of the equivalent ear canal volume which is related to the impedance of the occluded ear canal (e.g., Voss et al. 2000b). Tympanometry is performed in infants and young children as part of clinical audiology assessment. However, it is unclear whether differences in immittance characteristics from tympanometry could be useful in improving predictions of individual differences in the RECD. Children with larger ear-canal volumes have smaller RECD values (Feigin et al. 1989; Nelson-Barlow et al. 1988). The effects of other immittance characteristics on RECD, including admittance and tympanometric pressure remain unresolved. Average RECD data are available for children with normal middle-ear function, but normative data for children who have middle ear fluid, perforations, and tympanostomy tubes have not been published. An examination of RECD from 14 children with middle ear effusion indicated higher RECD values with middle ear dysfunction, but no systematic relationship between measures of ear-canal volume and RECD (Martin, Westwood, & Bamford, 1996). The lack of RECD data for children with middle-ear dysfunction is a major problem that can lead to errors in hearing-aid fitting, as these middle ear conditions are among the most frequently occurring health conditions for infants and young children (Leung & Wang 2017) and are known to affect the RECD and the accuracy of simulated hearing aid verification (McCreery et al. 2015).

Using a Bayesian Statistical Approach to model RECD

Advances in statistical techniques facilitate alternative analytic methods that do not require the same rigid assumptions as null-hypothesis significance testing based on frequentist approaches (Oleson, Brown, and McCreery, 2019). Frequentist statistical methods assume that a model must be tested against the probability that the effects of the model would be observed by chance. In the context of the current study, we could construct frequentist models to test the null hypothesis that the effect of including immittance data along with an average RECD is different than a model predicting a child's measured RECD based on the average RECD alone. If an audiologist is trying to decide whether to incorporate clinical immittance data into an algorithm to improve the proximity of an average RECD to the child's measured RECD when it cannot be measured, the audiologist is not interested in whether using the average RECD alone is different than using the average RECD and immittance together. Rather, audiologists would ask what the benefits of using both measures together would be in terms of magnitude of RECD errors that on hearing aid fitting outcomes.

A Bayesian statistical framework is ideal for providing probable parameter estimates and magnitude of uncertainty estimates introduced by different models. Frequentist models do not consider prior knowledge about the relationships between variables to avoid bias in the model. Because the goal of the current study was to quantify the relationships between individuals' middle-ear acoustics and RECD values, the distributions of parameter values (e.g., regression coefficients) that result from Bayesian statistical models are ideal for evaluating predictions and uncertainty resulting from using an average RECD alone compared to the average RECD with immittance data. Bayesian approaches calculate parameter probabilities directly from observed data. Bayesian analyses do not require calculation of p values or their associated confidence intervals, as with frequentist approaches (Kruschke & Liddell, 2018). Rather, uncertainty is quantified directly from the calculated distributions of parameters. This approach can be useful for applying the results of the model to clinical decisions about the range and likelihood of potential errors that could result from the two alternative approaches.

The goal of the current study was to determine if individual differences in immittance characteristics, including static admittance and ear-canal volume derived from 226 Hz tympanometry, could be used to predict measured RECD for children. We hypothesized that children with larger ear-canal volumes and greater admittance would have smaller RECD values. We also hypothesized that the model including immittance information would provide more accurate estimates of the child's measured RECD than an average RECD based on age.

Materials and Methods

Participants

Two-hundred sixty-six children with permanent hearing loss provided data. Children were recruited as part of the multicenter Outcomes of Children with Hearing Loss study (Moeller & Tomblin, 2015) and ranged in age from 7 months to 12 years. Inclusion criteria were that English had to be the primary language spoken in the home, and that the child could not have additional disabilities diagnosed prior to enrollment in the study. The mean better-ear pure tone average at 500, 1000, and 2000 Hz for the sample was 48.5 dB HL. Children with tympanostomy tubes or tympanic membrane perforations were excluded from this analysis. The number of visits with RECD data by the child's sex and age group are shown in Table 1. The procedures were approved by the IRB Boards of the participating institutions.

Table 1 –Number of study visits with RECD by Child's sex and age group							
Age	Child's Sex		Number of Visits with RECD				
	Female	Male	1	2	3	4	5 or more
1 year or less	16	28	15	18	4		
2 years	33	37	36	15	12	7	
3 years	52	47	31	27	21	15	5
4 years	55	66	42	42	22	12	2
5 years	80	68	44	41	41	17	5
6-9 years	232	231	41	117	55	81	56
10-12 years	84	105		2		84	16

Materials

Tympanometry was measured using either a Grason-Stadler TympStar (Eden Prairie, MN) or Welch Allyn Audioscope 2 (Skaneateles Falls, NY). Audioscan Verifit 1 or RM 500SL probe microphone systems (Dorchester, ON) were used to measure individual RECDs.

Procedure

All testing took place in a sound-treated audiometric test booth or mobile test van by a pediatric audiologist. Tympanometry was conducted with audiometry. Individual RECDs were measured with the child's earmold or an insert foam tip as part of hearing-aid verification . The child was seated approximately 2 feet from the verification system, and a probe microphone was placed in the ear canal approximately 10 mm past the entrance to the ear canal. A transducer was connected to the tubing of the earmold or insert foam tip. The earmold or foam tip was inserted over the probe microphone, and sound was delivered to the ear canal via the transducer. The transducer delivered a 60 dB SPL broadband noise signal to the child's ear for 10 seconds or until the acoustic response stabilized. The process was repeated for the opposite ear. The same measurement of broadband noise at 60 dB SPL was completed in the 2 cm^3 coupler that was used for hearing aid verification. The difference between the coupler response and the response measured in the child's ear canal was the RECD. The frequency-specific average RECD data for each child were derived based on the child's age at the time of the study visit from Bagatto et al. (2002). Middle ear status was classified based on admittance, tympanometric peak pressure, and equivalent ear-canal volume from the 226 Hz tympanogram for each ear. Normal middle ear status was classified as admittance ≥ 0.3 mL, tympanometric peak pressure > - 150 daPa, and an equivalent ear-canal volume of 0.4 – 2.0 cm^3. Ears were considered abnormal if one or more of these values were outside of the normal range (Alaerts, Luts, & Wouters, 2007).

Statistical analysis

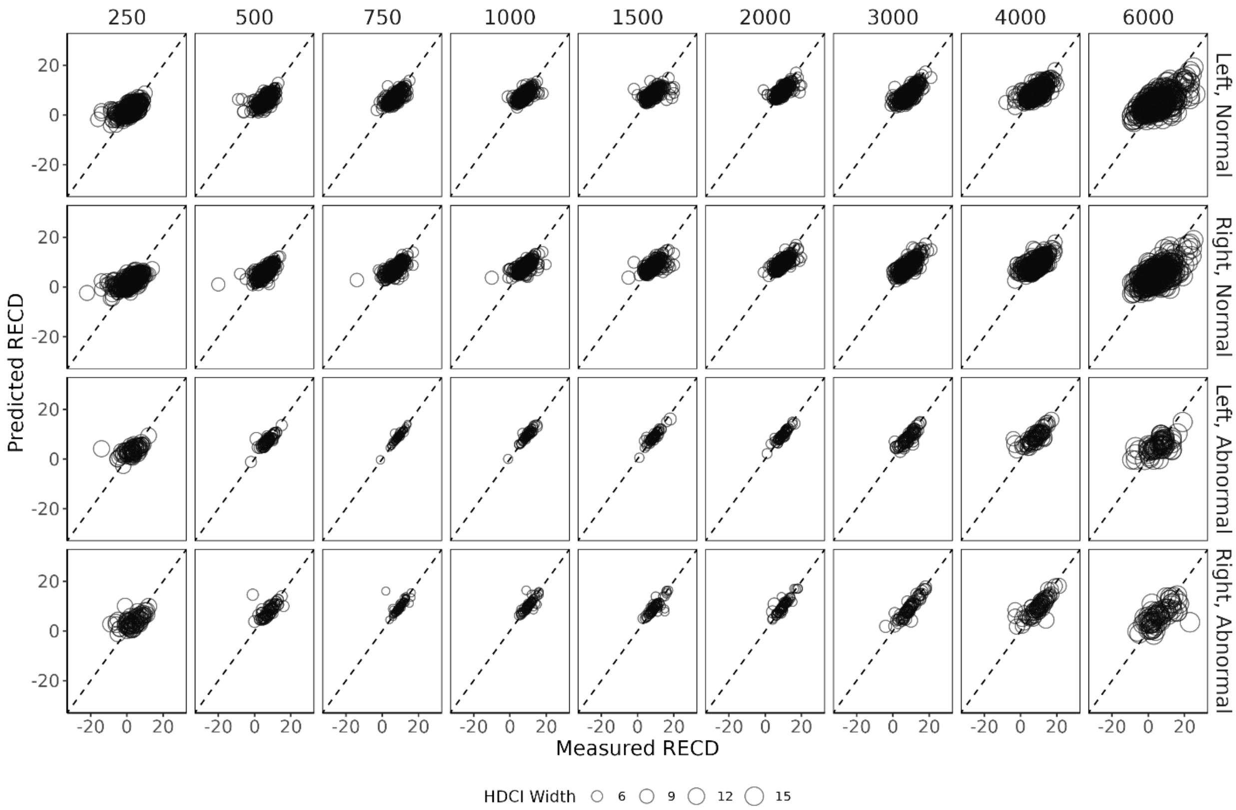
We conducted our analyses under a Bayesian framework as we were interested in estimating directly the most probable set of parameter values, including distributional parameters, that explain our data as well as quantifying the uncertainty surrounding parameter estimates. All models were constructed using the Stan programming language (Carpenter et al., 2017) through the cmdstanr (Gabry J, Češnovar R, 2021) and brms (Bürkner, 2017, 2018) packages in R statistical computing software (R Core Team, 2021).

To address our research questions about the potential benefits of incorporating individual measures of ear-canal acoustics from clinical tympanometry to enhance predictions of the child's RECD, we constructed a model of measured RECDs; with population-level effects of average RECD, frequency, middle-ear status (normal vs. abnormal), ear-canal volume (ECV), 226 Hz tympanometric peak pressure, 226 Hz admittance, and interaction terms for average RECD x frequency and middle-ear status x frequency. We standardized continuous predictor variables by subtracting the variable mean and then dividing by its standard deviation.

We included varying effects of frequency and middle-ear status, and group-level effects of subjects' individual ears and year of measurement. We estimated distributional effects of variance (σ) r and degrees of freedom for a Student's t distribution with varying effects of frequency grouped by middle-ear status. We evaluated and compared our immittance model with a Gaussian/Normal model with only average RECD, frequency, and their interaction as population-level effects using Pareto smoothed importance sampling leave-one-out cross-validation (PSIS-LOO; Vehtari, Gelman & Gabry, 2017). PSIS-LOO is a way of estimating pointwise out-of-sample predictive accuracy of a fitted Bayesian model. PSIS-LOO estimates the expected log predictive density (ELPD), which can be used to evaluate and compare different models relative to observed data. A difference in PSIS-LOO ELPD of 3-5 times greater than the standard error (SE) is considered a significant improvement. Comparing our models, our immittance model was a significantly better fit to the data relative to the average RECD and Frequency only Gaussian model with a difference in ELPD of 2632.1 (SE of 85.2) in favor of the immittance model.

RESULTS

Supplementary Figure 1 depicts immittance model predicted RECDs versus measured RECDs by frequency, ear, and middle ear status. In general, the model predictions of RECD were concentrated along the diagonal for frequencies from 500 Hz – 4000 Hz. Greater uncertainty of model estimates was observed at 250 Hz and 6000 Hz as evidenced by larger symbols off the diagonal line.



Supplementary Figure 1: Immittance model Predicted real-ear-to-coupler difference (RECD) plotted by measured RECD with rows of panels for ear (left vs. right) and middle ear status (normal vs. abnormal) and columns for each frequency in Hz. Perfect agreement between predicted and measured is indicated by the diagonal dashed line. Uncertainty is represented by the width of the 89% highest-density credible interval (HDCI) around the prediction and is depicted as the size of the circles with larger circles representing greater uncertainty of the prediction in dB.

There were no significant differences between ears for each subject, so further visualization are collapsed across ears. Figure 1 shows the difference between average RECD and measured RECD for the participants in the study. For 500 Hz – 3000 Hz, differences between average RECD and measured RECD was centered around 0 dB with a range of + 20 dB to – 10 dB. At 250 Hz, 4000 Hz and 6000 Hz, the average RECD was greater than the measured RECD.

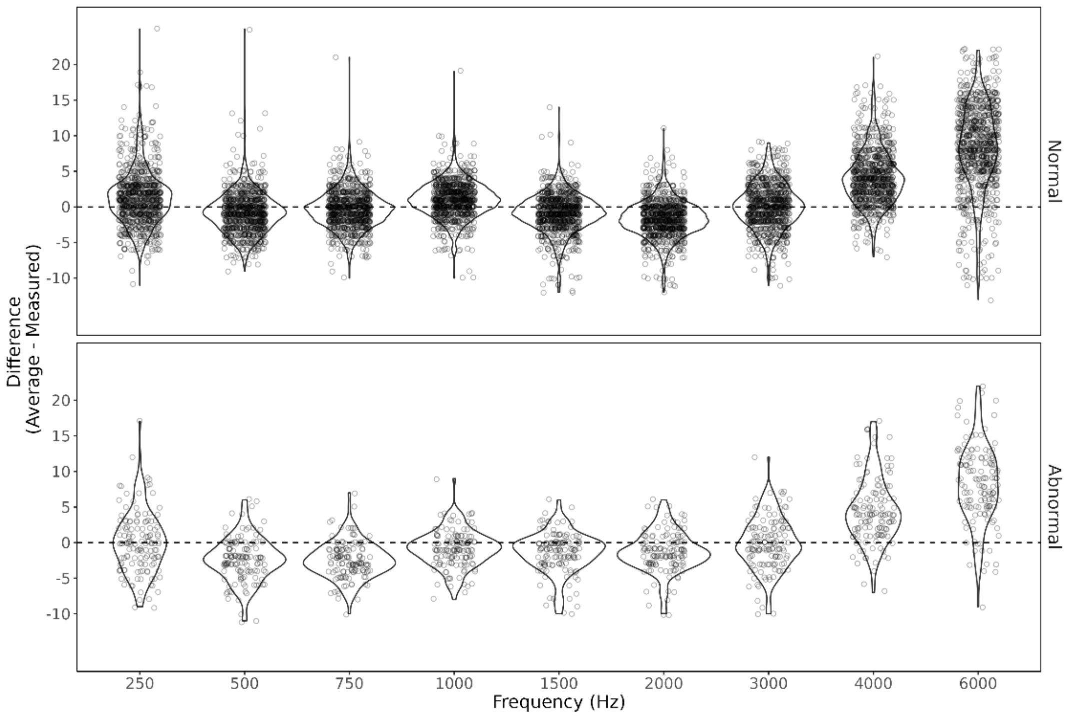


Figure 1: Violin plots of the differences between average and measured real-ear-to-coupler difference (RECD) in dB plotted by frequency for normal middle ear status (top panel) and abnormal middle ear status (bottom panel). Open circles represent individual data points. The sides of the violin plots are a symmetrical representation of the distribution of underlying values for each frequency.

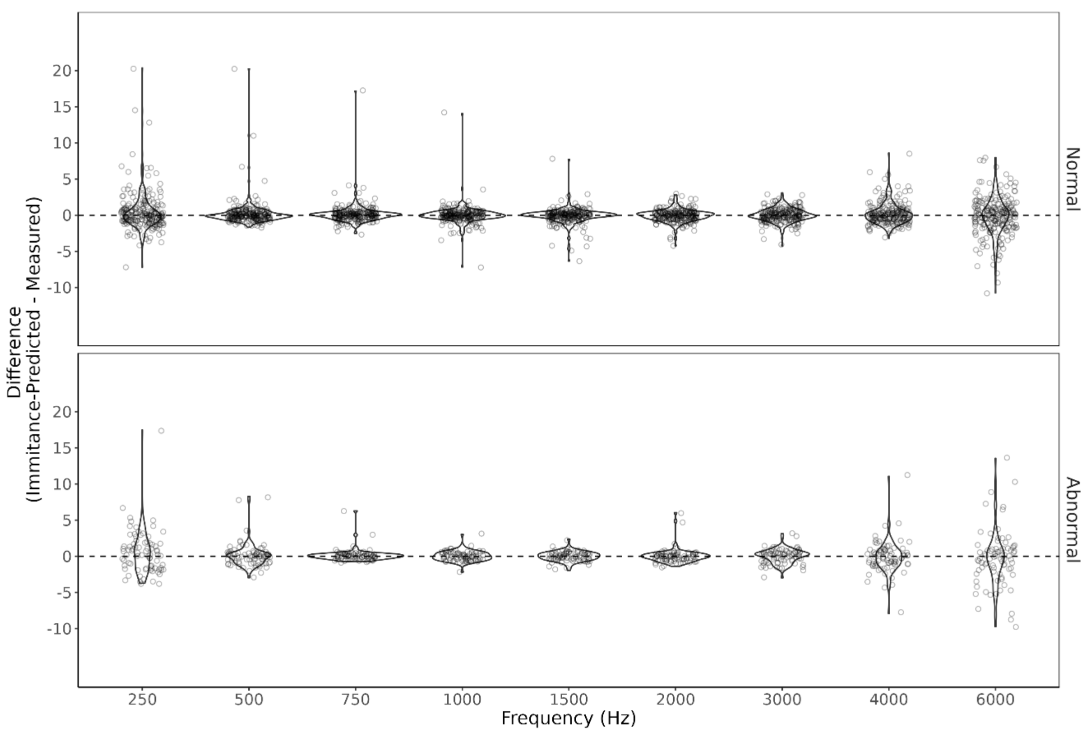


Figure 2: Violin plots of the differences between immittance-predicted and measured real-ear-to-coupler difference (RECD) in dB plotted by frequency for normal middle ear status (top panel) and abnormal middle ear status (bottom panel). Open circles represent individual data points. The sides of the violin plots are a symmetrical representation of the distribution of underlying values for each frequency.

Figure 2 shows the difference between immittance-predicted RECD and measured RECD. Differences were within +/- 5 dB between the immittance-predicted RECD and measured RECD. The largest differences between the immittance-predicted RECD and measured RECD were at 250 Hz and 6000 Hz, though the distribution of errors for the immittance-predicted RECD were more evenly distributed around 0 dB than for average RECD. The immittance-predicted RECD model had smaller differences from measured RECD and less variability than average RECD.

To further quantify the absolute magnitude of error and uncertainty from the immittance-predicted RECD, Figure 3 depicts the root mean square error (RMSe) of immittance-predicted RECDs by frequency and middle ear status. The dashed line is at 3 dB, which we chose as a meaningful degree of accuracy based on previous studies of test-retest reliability of the RECD procedure (Hatton & Munro, 2001; Bagatto et al, 2005). For children with normal middle ear status, the RMSe of the predicted RECD fell within 3 dB from 250 Hz – 4000 Hz with larger RMSe at 6000 Hz. For children with abnormal middle ear function, the distribution of RMSe had a much larger range indicating greater uncertainty when the middle ear status is abnormal for the model predictions of RECD. The width of the RMSe represents the distribution of values in the posterior distribution of the Bayesian model. For both models, the RMSe for frequencies between 500 Hz – 3000 Hz was less than 3 dB for children with either normal or abnormal middle-ear status, The RMSe for the immittance-predicted RECD was smaller than the average-RECD model by approximately 1 dB for from 500 to 6000 Hz.

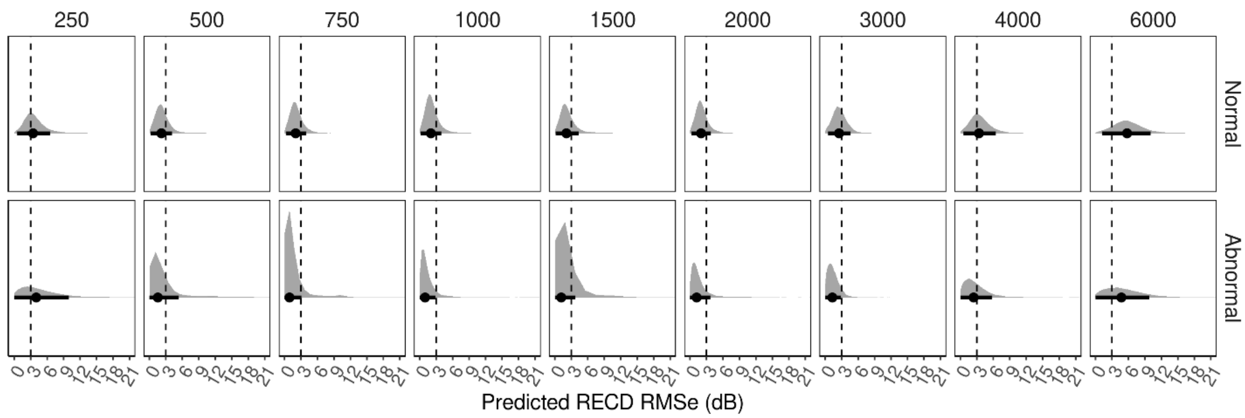


Figure 3: Root-mean-square error (RMSe) of approximation across frequency (columns) and middle ear status (normal – top row; abnormal – bottom row). Points represent median RMSe values, horizonal bars indicate the 89% highest-density credible interval (HDCI) around the median RMSe, and gray shaded regions indicate the distribution of RMSe.

The proportion of ears where each model would produce an estimate within 3 dB of the measured RECD was estimated to further assess the relative clinical accuracy of each model. Figure 4 shows the percentage of cases within 3 dB by frequency for each model by middle-ear status. The immittance-predicted RECD resulted in a higher proportion of cases within 3 dB of the measured RECD than the average RECD at every frequency except 6000 Hz. For children with normal middle ear status, the average RECD model was within 3 dB in 54.6% [89% CI 53.6, 55.3] of ears across frequency, whereas the proportion of ears within 3 dB for the immittance-predicted RECD was 69.6% [89% CI 68.9, 70.4]. Similarly for children with abnormal middle ear status, the average RECD model was within 3 dB in 50.6% of ears [89% CI 48.9, 51.8] whereas the immittance-predicted RECD was within 3 dB of measured RECD in 74.4% of ears [89% CI 71.8, 76.2].

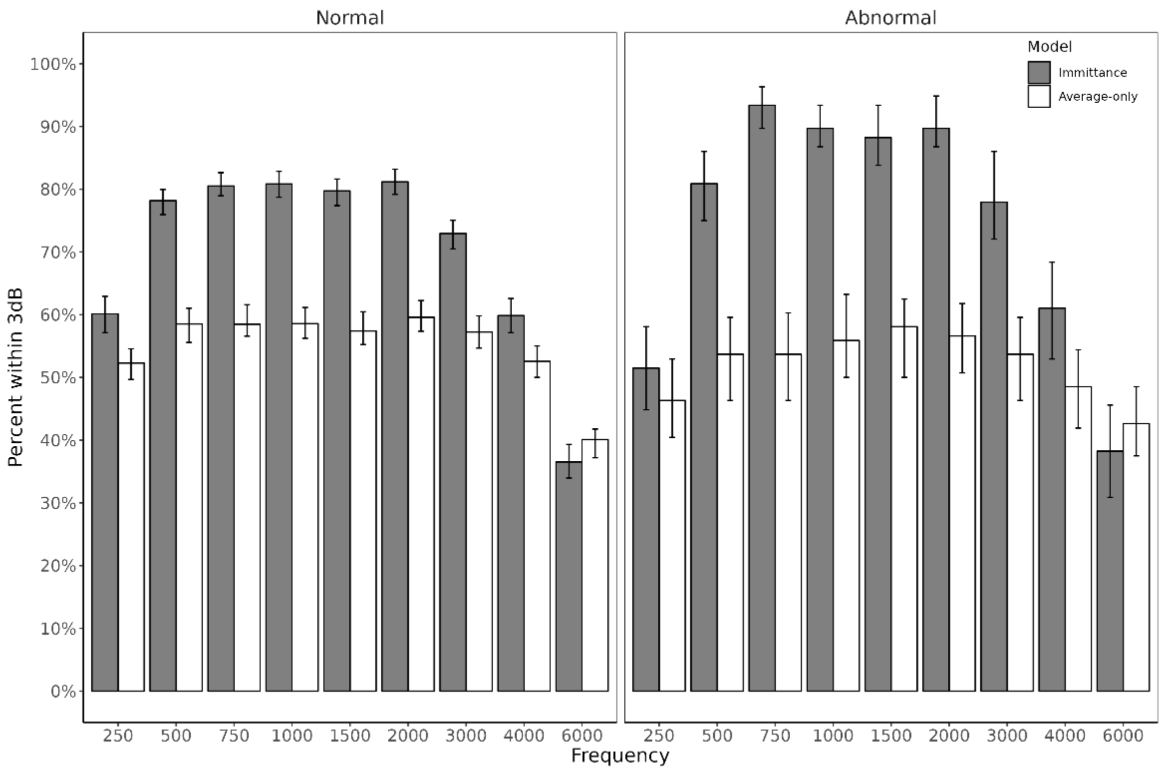


Figure 4: The percent of ears within 3 dB of the measured real-ear-to-coupler difference (RECD) by frequency (Hz) for immittance-predicted RECD (dark gray bars) and average RECD (white bars). The left panel is children with normal middle ear status and the right panel is abnormal middle ear status. The errors bars represent the 89% confidence interval.

Figure 5 shows the immittance-predicted RECD compared to the average RECD as a function of frequency and age in months, as well as the difference between immittance-predicted RECD and average RECD by age and frequency. The average RECD was within the 89% credible interval for the immittance-predicted RECD at each frequency across the age range from 6 – 132 months. As anticipated, both average RECD and immittance predicted RECD decrease as age increases for children with normal middle ears. For 250 Hz and frequencies above 1500 Hz, the average RECD does not change significantly after 60 months of age, whereas the immittance-model RECD for children with normal middle ear shows continued decreases across frequency consistent with maturation and growth of the ear canal. For children with abnormal middle ears, the immittance-predicted RECD shows a decrease followed by an increase across frequency that is not represented by the average RECD.

Conditional Effects

Conditional effects were calculated by holding all predictors, other than the variable of interest, at a constant value, the mean in this case. In this model, continuous predictors were standardized prior to modelling and are thus in standard deviation units with a mean of zero. The immittance-predicted RECD followed patterns that are consistent with previous acoustical models (Voss et al. 2000; Voss et al. 2005). The RECD decreased as age (-0.03; CI -0.13 to 0.06), ear-canal volume (-0.11; CI -0.17 to -0.05), tympanometric peak pressure (-0.09; CI -0.14 to -0.04), and static admittance (-0.17; CI -0.24 to 0.10) increased.

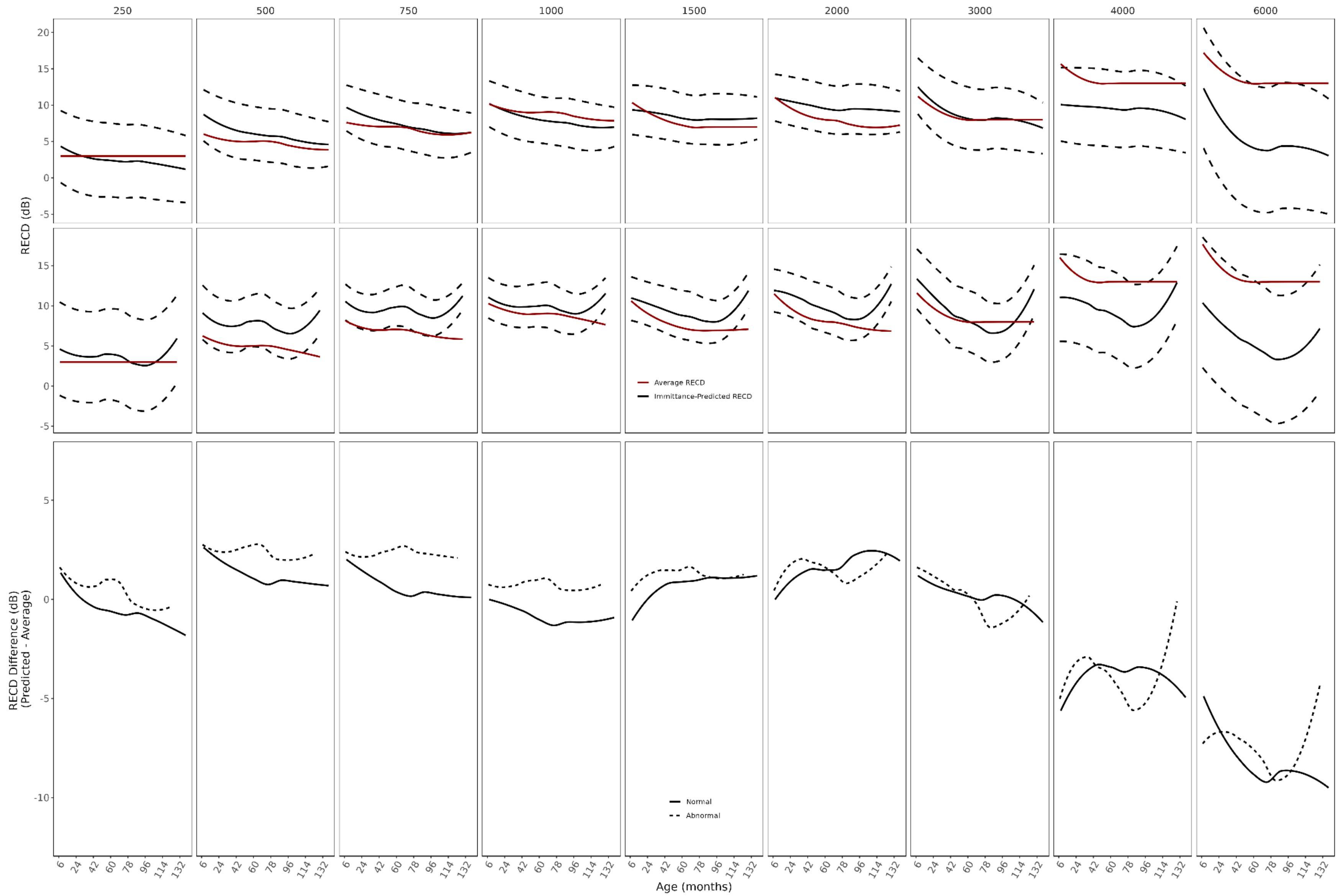


Figure 5: The immittance-predicted RECD as a function of age in months. Columns represent frequency (Hz) and the top two rows represent middle ear status (top panel – normal, bottom panel – abnormal). The red line in each plot represents the average RECD as a function of age and the solid line represents the mean prediction from the immittance model. The bottom row represents the difference in dB between the immittance-predicted and average RECD values by frequency across age. The dashed lines represent the range of the 89% credible interval for the immittance-predicted RECD model across age.

Discussion

In this analysis, we compared predictions of a child's measured RECD based on an age-based normative RECD values (average RECD model), which is the current clinical gold standard in cases where RECD cannot be measured, to a model that combined age-based average RECD with immittance characteristics from 226 Hz tympanometry (immittance-predicted RECD model). Our goal was to determine if incorporating tympanometric immittance data that reflect the acoustical properties of the ear canal and middle ear could improve the accuracy of hearing aid verification compared to average RECD in cases where the RECD cannot be individually measured. A strength of this study was that we used a Bayesian statistical approach to help quantify the probabilities and magnitude of clinical errors that exist from using average RECD or immittance-predicted RECD measures for children with both normal abnormal middle ear statuses.

We found that the immittance-predicted RECD model that incorporated 226 Hz tympanometry data led to a greater proportion of predictions within 3 dB of a child's measured RECD than a model that used only the average RECD values based on the child's age. The average RECD model resulted in predictions of RECD that were within 3 dB in 54.6% of cases with normal middle ears and 50.6% of cases with abnormal middle ear, whereas the immittance-predicted RECD was within 3 dB for 69.6% of cases with normal middle ears and 74.4% of cases with abnormal middle ears. Across frequencies, both average RECD and immittance-predicted RECD estimates were within 3 dB of measured RECD except at 250 Hz and 6000 Hz. Fewer than 50% of cases had model predictions of measured RECD that were within 3 dB at 250 Hz and 6000 Hz. These findings suggest that incorporating available immittance data from 226 Hz tympanometry for an individual child leads to more accurate estimates of ear-canal acoustics for most frequencies than relying on an average RECD for the child's age.

The finding that estimates of RECD from the immittance-predicted RECD model were more accurate than using the average RECD is consistent with predictions based on acoustical modelling from previous studies (Voss et al, 2000a) and studies that have examined the association between ear-canal volume and RECD (Feigin et al. 1989; Nelson-Barlow et al. 1988, but also see Martin, Westwood, & Bamford, 1996). Acoustic characteristics of the ear canal and middle ear are known to affect RECD due to individual differences in impedance (Voss et al. 2000a; Voss & Hermann 2005). The effects of immittance characteristics, including ear-canal volume, admittance, and tympanometric peak pressure were small, but had credible intervals that suggested that each impacted the RECD while controlling for other variables including age. Age had the smallest effect size of all predictors with a credible interval that included the null effect. The inclusion of admittance and tympanometric peak pressure, in addition to volume, may help to explain improvements in predicting RECD compared to previous studies that had included only ear-canal volume (Feigin et al. 1989; Nelson-Barlow et al. 1988). The immittance-predicted model further improved upon those predictions compared to the average RECD model for children with normal or abnormal middle ear status.

Although the immittance-predicted RECD was more accurate than using an average RECD, the results also show that using an average RECD also produces reasonable predictions of RECD in 50% of ears regardless of middle ear status. Recent studies of hearing aid fitting errors in children who did not consistently receive individualized hearing-aid verification suggest that more than half of children had a fitting error in one ear that was 5 dB or greater from 500 Hz – 4000 Hz (McCreery et al. 2013; McCreery et al. 2015). Both the average RECD and immittance-predicted RECD model produced estimates of ear-canal acoustics that would have led to lower fitting errors had they been used as part of the hearing aid verification process, even for children with abnormal middle ear status at the time of hearing aid verification. Immittance-predicted RECD offers an option with intermediate accuracy between the current gold standard of *in situ* or simulated *in situ* hearing-aid verification with a measured RECD and using an average RECD. However, the fitting errors from average RECD observed in this study were smaller than the fitting errors for children who did not have their hearing aids fitted with validated verification approaches in previous studies.

Clinical guidelines currently advise against using average RECD values in cases where children have abnormal middle ear function, tympanic membrane perforation, or tympanostomy tubes (Bagatto et al. 2005; Ontario Infant Hearing Program, 2019; American Academy of Audiology, 2013). This recommendation is because the normative sample of children from which average RECD were derived have had intact tympanic membranes and normal middle ear function. However, the average RECD was within 3 dB of the measured RECD in half of the cases for children with abnormal middle ears. Adding clinical immittance data improved the proportion of ears within 3 dB to almost 75%. The practice of completing *in situ* verification or measuring the child's RECD remains the most accurate method of verifying the output of the hearing aid when a child has middle ear dysfunction, a tympanic membrane perforation or tympanostomy tubes, or anatomical differences of the ear canal that might lead to an atypical ear-canal volume compared to children who are the same age. However, these results provide support for the use of average RECD or immittance-predicted RECD in cases of abnormal middle ear function with an intact tympanic membrane where in situ verification or measured RECD is not feasible. The benefits of applying an immittance-predicted RECD for children with tympanic membrane perforations or tympanostomy tubes were not evaluated in this study but should be examined in future studies.

For the average RECD and immittance-predicted RECD models, the estimation of measured RECD at 6000 Hz was generally poorer than other frequencies, indicated by large RMSe values, broad credible intervals, and less than half of cases within 3 dB of the measured RECD. In general, the measured RECD values at 6000 Hz in these analyses were lower than the average RECD normative values from the published literature. This discrepancy between the measured RECD and average RECD at 6000 Hz is likely due to standing waves in the ear canal at the position of the probe microphone related to the cancellation of sound and reflections of sound from the tympanic membrane (Dirks & Kincaid, 1987; McCreery et al. 2009). As the bandwidth of hearing aids increases, the impact of these discrepancies at 6000 Hz for hearing-aid verification are likely to affect estimates of hearing aid output in clinically meaningful ways (Van Eeckhoutte et al 2020). The results indicate that using the average RECD or immittance-predicted RECD may not provide accurate predictions of the measured RECD at or above 6000 Hz. The application of wideband acoustic immittance, which characterizes the middle ear across a broader range of frequencies than 226 Hz tympanometry, and the use of wideband RECD (wRECD; Vaisburg et al. 2018) may help to improve the relationship between immittance characteristics and predictions of ear-canal acoustics at higher frequencies.

Clinical implications, limitations, and directions for future research

The main finding that incorporating immittance data from 226 Hz tympanometry can improve predictions of RECD compared to the average RECD has implications for clinical practice. Age-related average RECD may be used in 25-40% of clinical visits for hearing-aid verification for infants and young children (Moodie et al. 2016; McCreery et al. 2015). In those instances, generating a predicted RECD based on the child's 226 Hz tympanometry provides a more accurate estimate of ear canal acoustics than using the average RECD alone for children regardless of middle ear status, but particularly for children with abnormal middle ear function. Because 226 Hz tympanometry is easy to obtain and widely available, this approach warrants further exploration in a clinical context to develop tools and assess the impact of these predictions on the accuracy of hearing aid fittings. The statistical model developed in this study could be incorporated into clinical hearing aid verification systems or used in a stand-alone software implementation to generate an immittance-predicted RECD in cases where the RECD cannot be directly measured. A clinical implementation of this sort would require further validation prior to clinical adoption.

Equivalent ear-canal volume measured during tympanometry is different than the residual ear-canal volume that occurs with coupling to an earmold, which could increase the variability of the immittance-predicted RECD. Additionally, the 226 Hz tympanometry data that were incorporated into the immittance-predicted RECD model characterizes the outer and middle ear at a single, low frequency. As noted above, the immittance-predicted RECD model performed most poorly at 6000 Hz. The RECD is a broadband measurement and may benefit from the use of a broadband measure of outer and middle ear immittance using available techniques such as wideband acoustic immittance. Tympanometry also pressurizes the ear canal to characterize the admittance and relative pressure of the middle ear, but RECD measurements are not completed under pressurized conditions. Pressurizing the ear canal can influence the acoustic characteristics and sound level in the ear canal. Wideband acoustic immittance can be conducted at ambient pressure like the RECD and may more accurately predict the RECD. Future research should consider the impact of unpressurized wideband acoustic immittance estimates of outer and middle ear function to determine if further improvements in RECD prediction can be achieved.

Finally, although the RECD is not often measured in adult hearing aid users, an average adult RECD is used to convert dB HL thresholds measured with insert earphones to dB SPL thresholds for generation of prescriptive targets and hearing aid verification. Individual differences in ear-canal acoustics on hearing aid output are measured directly with adults using *in situ* verification, but the potential improvements in accuracy of thresholds and prescriptive targets by applying this approach with adults would require further investigation.

Conclusions

An immittance-predicted RECD model based on 226 Hz tympanometry produced smaller differences and a larger proportion of estimates within 3 dB of the measured RECD than the average RECD model for children with normal and abnormal middle ear statuses. Both average RECD and immittance-predicted RECD produced differences from measured RECD that were smaller than if hearing aid verification had not been conducted. These findings support the conclusion that clinical immittance measures improved the accuracy of predictions of RECD in children. The models used to apply clinical immittance data to improve predictions of RECD should be incorporated into clinical practices for hearing aid fitting in children to improve the accuracy and safety of hearing aid verification for children with hearing loss.

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