JASA ARTICLE

Predicting wideband real-ear-to-coupler differences in children using wideband acoustic immittance

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ABSTRACT:
Individual differences in ear-canal acoustics introduce variability into hearing aid output that can affect speech audibility. Measuring ear-canal acoustics in young children can be challenging, and relying on normative real-ear-to-coupler difference (RECD) transforms can lead to large fitting errors. Acoustic immittance measures characterize the impedance of the ear and are more easily measured than RECD. Using 226 Hz tympanometry to predict the RECD is more accurate than using age-based average RECD values. The current study sought to determine whether wideband acoustic immittance measurements could improve predictions of wideband real-ear-to-coupler difference (wRECD). 150 children ages 2–10 years with intact tympanic membranes underwent wRECD and wideband acoustic immittance measures in each ear. Three models were constructed to predict each child's measured wRECD: the age-based average wRECD, 226 Hz admittance wRECD, and wideband absorbance wRECD. The average age-based wRECD model predicted the child's measured wRECD within 3 dB in 62% of cases, but both the 226 Hz admittance and wideband absorbance wRECD were within 3 dB in 90% of cases. Using individual 226 Hz or wideband absorbance to predict wRECD improved the accuracy and precision of transforms used for pediatric hearing aid fitting.
 https://doi.org/10.1121/10.0020660

(Received 17 February 2023; revised 24 July 2023; accepted 30 July 2023; published online 15 August 2023)
[Editor: Matthew J. Goupell] Pages: 991–1002

I. INTRODUCTION

Electroacoustic verification of hearing aids is essential for providing appropriately fitted amplification for children with hearing loss and ensuring that speech is consistently audible. Over the last two decades, hearing aids have been fitted for infants with hearing loss within the first few months of life, to provide access to the acoustic cues that are needed to support spoken language development (Halpin *et al.*, 2010; Holte *et al.*, 2012). *In situ* probe microphone measurements of hearing aid output in the ear canal are the most accurate method of verifying speech audibility across a range of input levels and ensuring that the maximum output of the hearing aid is safe (Cox and Alexander, 1990; Bagatto *et al.*, 2005). Infants and young children, however, are often unable to cooperate or remain sufficiently quiet to allow multiple measurements of hearing aid output in the ear canal (Bagatto *et al.*, 2016; McCreery *et al.*, 2015). As an alternative when *in situ* probe microphone measures cannot be completed, an acoustic transform, known as the real-ear-to-coupler difference (RECD; Bagatto *et al.*, 2002), can be measured to relate the child's ear-canal acoustics to a standard coupler. Measurements of RECD are used to incorporate a child's individual ear-canal acoustics into hearing aid output measurements in the coupler.

However, nearly 40% of infants and young children are unable to cooperate for an individualized measure of their RECD (Bagatto *et al.*, 2016; McCreery *et al.*, 2015). In cases where the RECD cannot be measured, an age-related average RECD can be used, but individual variability in ear-canal acoustics for children who are the same age can introduce fitting errors of ±10–15 dB (Feigin *et al.*, 1989; Bagatto *et al.*, 2002). In a recent study (McCreery *et al.*, 2015), nearly 50% of children with hearing loss had a fitting error greater than 5 dB for the frequency range (500–4000 Hz) that is most important for speech audibility. Fitting errors were larger in cases where an average RECD was used (8 dB) compared to fitting where the child's measured RECD was used to fit the hearing aid (5 dB). Errors can be even more substantial when hearing aids are fitted with average RECD values for children with abnormal middle-ear function, including otitis media (Martin *et al.*, 1996) and tympanostomy tubes (Martin *et al.*, 1997) or tympanic membrane perforations (Martin *et al.*, 2001). To date, average RECD normative data have been derived only from children with normal middle-ear function, which contributes

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to these inaccuracies when average RECD data are used to fit hearing aids for children with abnormal middle-ear function.

The potential for over- or under-amplification in cases where an individual RECD cannot be measured has led to the exploration of alternative methods for estimating individual differences in ear-canal acoustics. In ears with intact tympanic membranes, normal middle-ear status, and roughly symmetrical ear-canal anatomy, measurements of RECD in one ear can be reasonably applied to the opposite ear as the two ears are correlated and within ±3 dB in most cases (Munro and Buttfield, 2005). However, measuring a single RECD still requires cooperation from the child and is not possible in many cases. Other studies have examined the use of individual physical characteristics that are easier to measure or more readily available in medical settings, including an individual's height, weight, and head circumference, as proxy variables to predict individual differences in RECD. For example, an evaluation of height, weight, and head circumference as predictors of individual RECD in 68 children who were 3–11 years old indicated that a child's head circumference was a statistically significant predictor of their RECD (Blumsack *et al.*, 2014). A follow-up analysis of head circumference to predict individual differences in RECD that included 278 children from 1 month to 11 years of age and 109 adults showed that head circumference had roughly the same predictive utility as age for individual differences in the RECD (Watts *et al.*, 2020). While head circumference may be easier to measure than using a probe microphone to measure the RECD in the ear canal of an individual child, head circumference produces similar fitting errors as using age-related RECD normative data.

The use of clinical middle-ear immittance data to predict individual differences in ear-canal acoustics for children has also been examined as an alternative to individual measures of RECD. Single-frequency tympanometry and wideband acoustic immittance characterize the impedance of the ear canal and middle-ear system by measuring relative sound absorbance using a probe with a receiver and a microphone. The impedance at the tympanic membrane alters the sound levels in the ear canal (Zwislocki 1962), which can lead to individual differences in ear-canal sound levels, even when the middle ear is healthy and intact. The effects of impedance on ear-canal sound levels with transducers used for audiological assessment suggest that individual differences in impedance of the ear canal and middle ear play a large role in the variability in measured sound pressure level in the ear canal. In two papers, Voss and colleagues modelled impedance changes related to specific middle-ear pathologies that predicted individual differences between ear-canal sound levels and coupler measures of up to 35 dB for insert earphones (Voss *et al.*, 2000b) and then confirmed the predictions of these models in adult patients with these pathologies (Voss *et al.*, 2000a). A follow-up study examined differences between infants and adults across transducers and found differences in ear-canal sound levels that were up to 15 dB between infants and adults based on the ear-canal size and geometry, as well as the impedance characteristics of the outer and middle ear (Voss and Herrmann, 2005). Thus, clinical immittance measures, such as tympanometry and wideband acoustic immittance, that characterize the equivalent volume and impedance and are more easily measured in infants and young children might provide a way to predict an individual RECD when it cannot be measured as part of hearing aid verification.

Predictions of RECD based on 226 Hz tympanometry have shown mixed results in previous studies. Nelson-Barlow *et al.* (1988) correlated the equivalent ear-canal volume derived from 226 Hz tympanometry to the peak amplitude of the RECD for 15 children and 15 adults with hearing loss. Small to moderate correlations ($r = 0.23$–0.43) were reported for ear-canal volume and RECD for children, depending on the coupler used for the RECD. A later study by Feigin *et al.* (1989) showed that ear-canal volume accounted for nearly half of the variance in RECD measures from 300 to 4000 Hz. The authors concluded that the relationship between RECD and ear-canal volume was not sufficiently strong to serve as a clinical predictor of individual differences in ear-canal acoustics for children or adults. In another study (Martin *et al.*, 1996), the relationship between ear-canal volume derived from 226 Hz tympanometry and the peak of the RECD was examined for 14 young children with flat tympanograms (no peak in the tympanogram >0.1 ml from −200 to + 200 daPa). The RECD values were 3.5 dB higher in children with flat tympanograms, but the correlation between ear-canal volume and the peak of the RECD was small ($r = 0.15$) and not statistically significant. Together, these studies suggest that ear-canal volume derived from 226 Hz tympanometry is not sufficient to accurately predict individual differences in ear-canal acoustics. The association between ear-canal acoustics and ear-canal volume in previous studies may have been limited by small sample sizes that precluded any associations between ear-canal volume and ear-canal acoustics or reliance on the correlation of ear-canal volume with the overall peak of the RECD averaged across frequencies.

More recently, we used a large dataset of 226 Hz tympanometry and RECD data from a longitudinal study of children with hearing loss (Moeller and Tomblin, 2015) to determine whether using a larger sample of children across a wider age range and a multivariate Bayesian statistical model could help to improve predictions of RECD based on clinical immittance measures (McCreery *et al.*, 2023). Data from 2491 visits of 266 children between the ages of 7 months and 12 years who had intact tympanic membranes with both normal and abnormal middle-ear status were collected. We used a Student's *t* model to generate model parameter estimates and associated uncertainty for an immittance-predicted RECD for each child based on age, equivalent ear-canal volume, tympanometric peak pressure, and static admittance from 226 Hz tympanometry. One of the benefits of the Bayesian modeling approach for this research question is that the model parameters allowed us to derive frequency-specific RECD and estimates of uncertainty for each ear of each child, which was not possible in previous studies that used correlational or frequentist statistical approaches. Immittance-predicted RECDs were compared to the child's measured RECD and an age-based average RECD to quantify the magnitude of the relative fitting error and uncertainty that would result from using either age-based average RECD or immittance-predicted RECD in place of the child's measured RECD. The age-based average RECD was within 3 dB of the measured RECD in approximately 50% of cases regardless of the child's middle-ear status. The immittance-predicted RECD was within 3 dB in 69% of cases where the child had normal middle-ear function and 74% of cases where the child had abnormal middle-ear function. A frequency-specific analysis of the immittance-predicted and average RECD indicated that both alternatives to the child's measured RECD had larger errors and greater estimates of uncertainty at 4000 and 6000 Hz than at lower frequencies.

Although the immittance-predicted RECD produced more accurate estimates of a child's measured RECD than using age-related normative RECD values, there may be limitations to using an immittance measure that characterizes the ear canal and middle ear at a single, stiffness-dominated low frequency under pressurization, given the RECD is measured at ambient pressure across a wide range of frequencies. In contrast to single-frequency tympanometry, wideband acoustic immittance uses broadband stimuli to characterize the impedance of the ear canal and middle ear across the same range of frequencies that are measured with the RECD (Hunter *et al.*, 2013). Further, recent increases in the high frequency bandwidth of hearing aids (Van Eeckhoutte *et al.*, 2020) have necessitated an instantiation of the RECD that can characterize ear-canal acoustics at frequencies above 6000 Hz, known as the wideband real-ear-to-coupler difference (wRECD; Vaisberg *et al.*, 2018). The wRECD is measured in a 0.4 cm^3 coupler instead of a 2 cm^3 coupler to provide higher output above the microphone noise floor at frequencies above 5000 Hz [International Electrotechnical Commission (IEC), 2006]. The prediction of wRECD from immittance measures may require data from a broader range of frequencies than are assessed with 226 Hz tympanometry.

In summary, the current practice of characterizing ear-canal acoustics for hearing aid verification in children with hearing loss relies on individual measurement of the RECD or wRECD, which is not always possible. Clinical tympanometric measures have shown promise for characterizing ear-canal acoustics when the RECD cannot be measured, but the application of wideband acoustic immittance for predicting wRECD has not been assessed or compared with single-frequency tympanometry as a predictor of wRECD. In this study, we used wideband acoustic immittance and wRECD data from a large group of children to determine whether immittance-predicted wRECD from a Bayesian statistical model produces estimates of measured wRECD that could lead to improved hearing aid fitting accuracy for children when the wRECD cannot be directly measured due to the child's limited cooperation or other factors.

II. METHODS

A. Participants

150 children were recruited and provided data for this analysis, including children with varying degrees of hearing loss and children with normal hearing. Children ranged in age from 2 to 10 years. Inclusion criteria for the study were that English had to be the primary language spoken in the home and that the child must have had normal outer-ear and ear-canal anatomy. A total of 280 ears were included in the analysis. The sample included 75 males and 68 females. Institutional Review Board (IRB) approval was obtained for the procedures completed by the IRB at Boys Town National Research Hospital (Omaha, NE). Children were monetarily compensated and received a book or a prize for their participation.

B. Materials

Wideband acoustic immittance was measured using the Interacoustics Titan (Eden Prairie, MN) probe and the clinical Titan Suite software. Wideband acoustic immittance was completed in response to a click stimulus (220–8000 Hz) in a pressurized condition with down-swept pressure ranging from +200 to −300 at a rate of approximately 100 daPa/s. The system was calibrated yearly by a technician per manufacturer recommendations. Wideband acoustic immittance data were exported from the clinical Titan Suite into XML files, which were then parsed using R statistical software (R Core Team, 2022) to extract the measures of interest. Extracted measures included the absorbance response at or nearest to 0 daPa (ambient absorbance) as well as the tympanometric peak pressure, the peak static admittance nearest to 226 Hz, and the equivalent ear-canal volume. Ambient absorbance was chosen over absorbance at tympanometric peak pressure given that wRECD measures are collected at ambient pressure. Absorbance is the ratio of the absorbed portion of the click stimulus to the incident stimulus. Absorbance responses were inspected for the presence of air leaks using criteria described in Groon *et al.* (2015) based on absorbance <0.29 between 200 and 500 Hz. Absorbance responses were averaged across frequency in 1/6 octave bands for analysis. An Audioscan Verifit II probe microphone system (Dorchester, Canada) was used to measure individual wRECD in 1/3 octave bands from 250 to 12 500 Hz.

C. Procedure

Otoscopy was completed to confirm the absence of occlusive cerumen or other ear-canal anomalies. Wideband acoustic immittance was conducted once in each ear, and measures of ear-canal volume, peak static admittance at 226 Hz, tympanometric peak pressure, and ambient absorbance nearest to 0 daPa were extracted. Wideband acoustic immittance measures were repeated only if the child was noisy during the measurement. Middle-ear status was classified as normal or abnormal based on ear-canal volume, admittance, and tympanometic peak pressure using the 226 Hz tympanogram derived from the pressurized wideband acoustic immittance measurement. An equivalent ear-canal volume of 0.4–2.0 cm^3, admittance of $\geq$0.3 ml, and tympanometric peak pressure ≥ -150 daPa on 226 Hz tympanometry were the criteria for normal middle-ear status. Abnormal middle-ear status was given to data from ears where one or more of the equivalent volume, admittance, and/or tympanometric peak pressure were outside of the normal range (Alaerts *et al.*, 2007).

Individual wRECDs were measured for all children. The participant was seated approximately 2 ft from the probe microphone verification system. A flexible probe microphone was placed into the ear using the constant insertion method (Moodie *et al.*, 1994), where the probe is placed in the ear canal approximately 10 mm past the medial termination of a pediatric insert foam plug. The transducer that delivered sound into the ear canal was connected to a foam insert. A Verifit 2 default RECD stimulus of 60 dB SPL pink-shaped noise was delivered to the ear through the insert foam tip for approximately 10 s or until the response stabilized. The same broadband noise was presented via the transducer to a 0.4 cm^3 coupler used for hearing aid verification. The wRECD was the difference between the 0.4 cm^3 coupler response and the response measured in the child's ear canal. Frequency-specific age-based average wRECD data for each child were based on the child's age at the time of the study visit taken from the normative RECD data in Audioscan Verifit 2.

D. Statistical analyses

We conducted our analyses under a Bayesian framework as we were interested in directly estimating 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 and Češnovar, 2021) and brms (Bürkner, 2017) packages in R statistical computing software (R Core Team, 2022).

To address our research questions about the potential benefits of incorporating individual measures of ear-canal acoustics from standard clinical tympanometry as well as wideband acoustic immittance to enhance predictions of the child's wRECD, we constructed three models to predict each child's measured wRECDs. The average age-based wRECD model included population-level effects of frequency, age, and average wRECD. The 226 Hz admittance wRECD model was generated as a replication of the model completed in our previous study (McCreery *et al.*, 2023) and included the same effects of the average age-based wRECD model but added data from 226 Hz tympanometry derived from the wideband acoustic immittance measure, including ear-canal volume (ECV), the peak static admittance nearest to 226 Hz, and interaction terms for average wRECD $\times$ frequency, middle-ear status $\times$ frequency, and middle-ear status $\times$ absorbance. The wideband absorbance wRECD model included the same predictors as the 226 Hz admittance model but included an effect for frequency-specific absorbance at ambient pressure in place of the 226 Hz admittance at tympanometric peak pressure. All models included varying (group-level) effects of frequency and middle-ear status by subjects' individual ears. We estimated distributional effects of variance (σ) and degrees of freedom (ν) with varying effects of frequency and middle-ear status.

III. RESULTS

We compared the wideband absorbance wRECD, 226 Hz admittance wRECD, and average age-based wRECD models using Pareto smoothed importance sampling leave-one-out cross-validation (PSIS-LOO; Vehtari *et al.*, 2017) to estimate the expected log predictive density (ELPD) and evaluate and compare the fit of the three models to the 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 wideband absorbance wRECD model was a significantly better fit to the data relative to the average age-based wRECD model with a difference in ELPD of 1452.2 (SE of 55.6) in favor of the wideband absorbance wRECD model. However, ELPD was equivocal between the 226 Hz admittance wRECD model and the wideband absorbance wRECD model (ELPD difference: 1.2, SE: 8.1), consistent with no differences in model fit between the two models that included individual immittance data.

Figure 1 shows the wideband absorbance wRECD model predictions as a function of the measured wRECD. In general, the model predictions of wRECD were concentrated along the diagonal for frequencies from 250 to 4000 Hz for children with normal and abnormal middle-ear function, indicating good agreement between model predictions and measured wRECD with low uncertainty. Greater uncertainty of model estimates was observed at 6000 and 8000 Hz, as evidenced by larger circles and circles off the diagonal line. The mean difference between ears was 0.08 dB (SE: 3.4 dB), so additional figures display model predictions collapsed across ears of the same participants.

Figure 2 shows the differences between the average wRECD and measured wRECD as a function of frequency and middle-ear status. The interquartile range of the differences between the average age-based wRECD model predictions and measured wRECD were within $\pm$5 dB for frequencies from 250 to 3000 Hz and $\pm$10 dB for 4000–6000 Hz. Figure 3 shows the differences between the wideband absorbance wRECD model and measured wRECD as a function of frequency and middle-ear status. The differences between the average age-based wRECD model predictions and measured wRECD were within $\pm$2 dB for frequencies from 250 to 8000 Hz. The wideband

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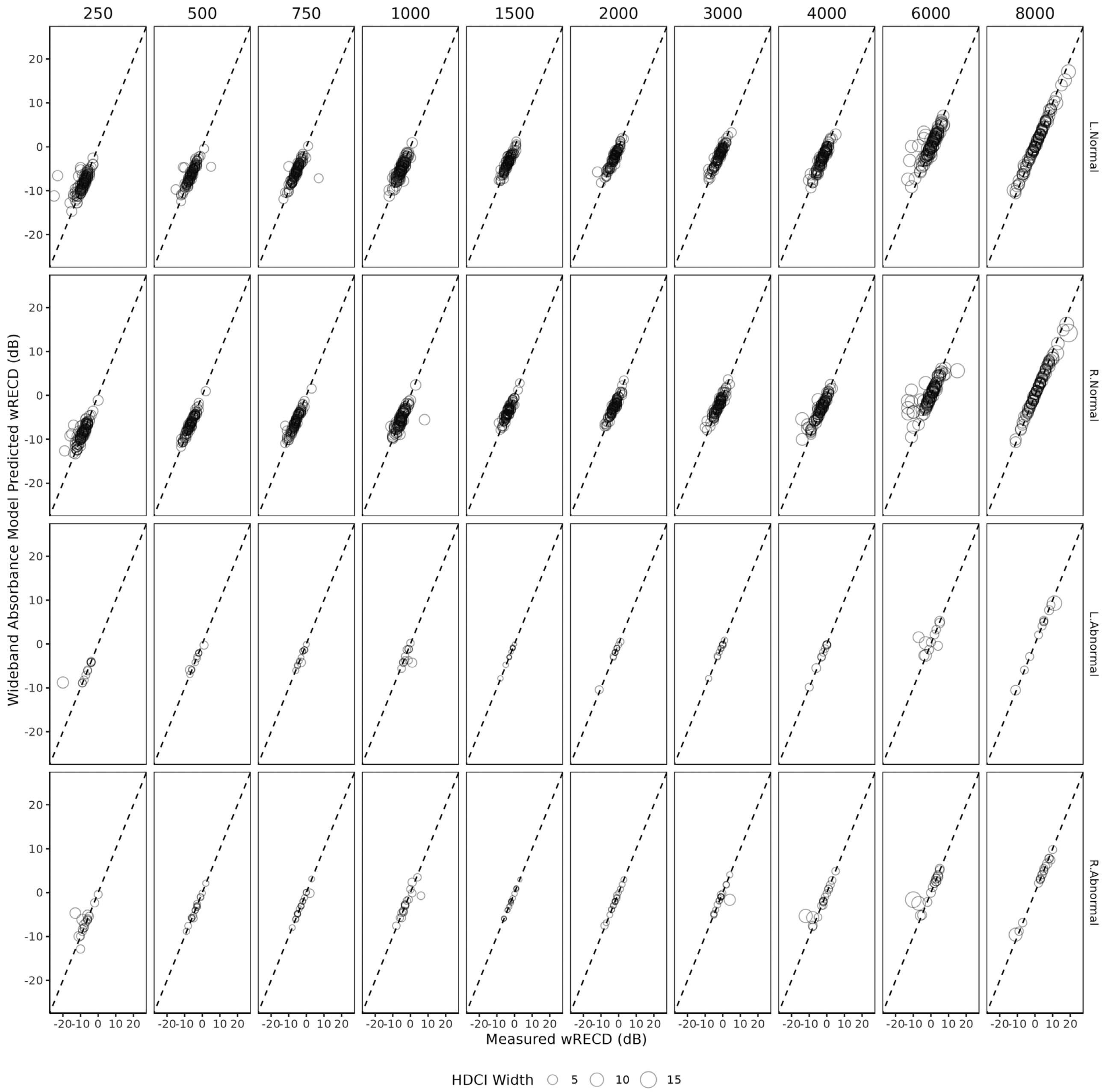

FIG. 1. Wideband absorbance wRECD vs measured wRECD by frequency, ear (R, right; L, left), and middle-ear status (normal vs abnormal). Perfect prediction is indicated by the diagonal dashed line. Uncertainty is represented by the width of the 89% highest-density CI around the prediction and is depicted as the size of the circles.

absorbance model resulted in much smaller interquartile ranges for predictions of each child's measured wRECD than the average age-based wRECD model.

To further quantify the differences between the three models, the root mean square error (RMSE) of predicted wRECDs for predicting each child's measured RECD was calculated by frequency and middle-ear status. A criterion of 3 dB was chosen as a meaningful degree of accuracy based on previous studies of test-retest reliability of the RECD (Bagatto *et al.*, 2005) and wRECD (Vaisberg *et al.*, 2018) procedures. Figure 4 shows the RMSE by frequency and model by middle-ear status. An RMSE of 3 dB or less would indicate a degree of accuracy between predicted and actual wRECD within the limits of test-retest, while an RMSE greater than 3 dB would indicate a prediction outside of the test-retest reliability for measured wRECD. For children with normal or abnormal middle-ear status, the RMSE of the 226 Hz admittance and wideband absorbance wRECD models fell within test-retest reliability of the measured wRECD from 250 to 6000 Hz with larger errors at 8000 Hz for both models. For the average age-based wRECD model, the RMSE was larger and had a broader credible interval (CI) range, indicating greater uncertainty in wRECD estimates for both normal and abnormal middle-ear status

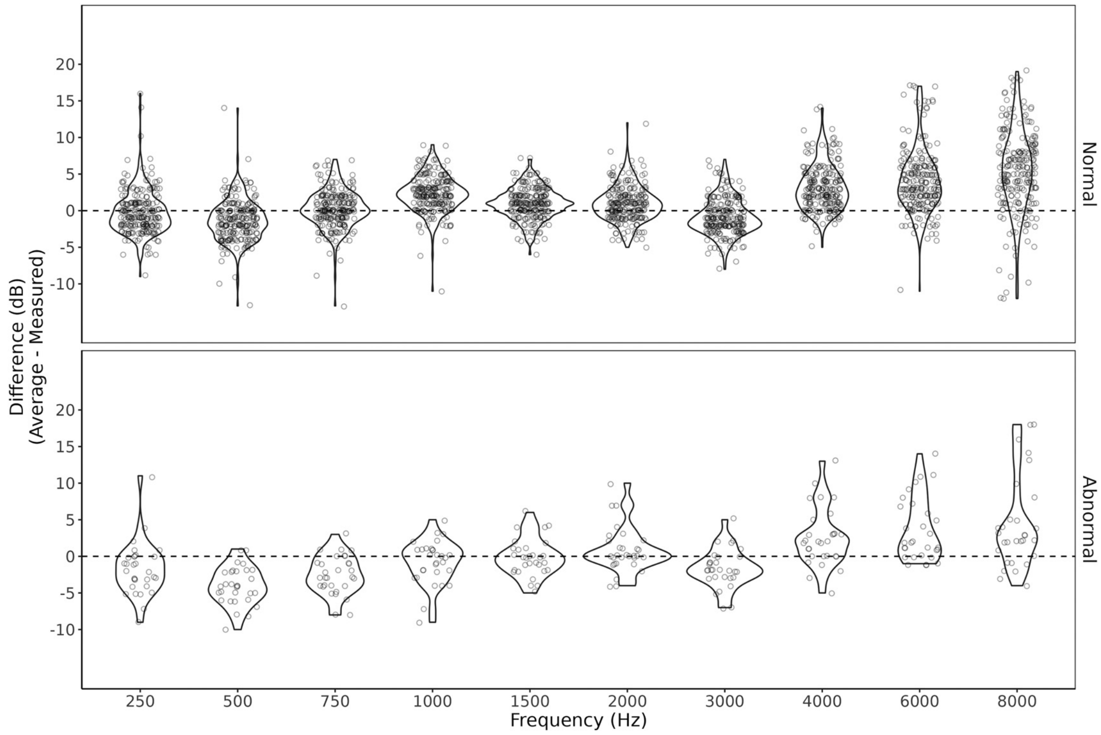

FIG. 2. Violin plots of the difference between the average age-based wRECD model and measured wRECD by frequency and middle-ear status (upper panel, normal middle-ear status; lower panel, abnormal middle-ear status). Circles represent individual differences at each frequency between model predictions and measured wRECD. The violin plot provides a symmetrical representation of the distribution of values at each frequency with the vertical boundaries representing the range of differences.

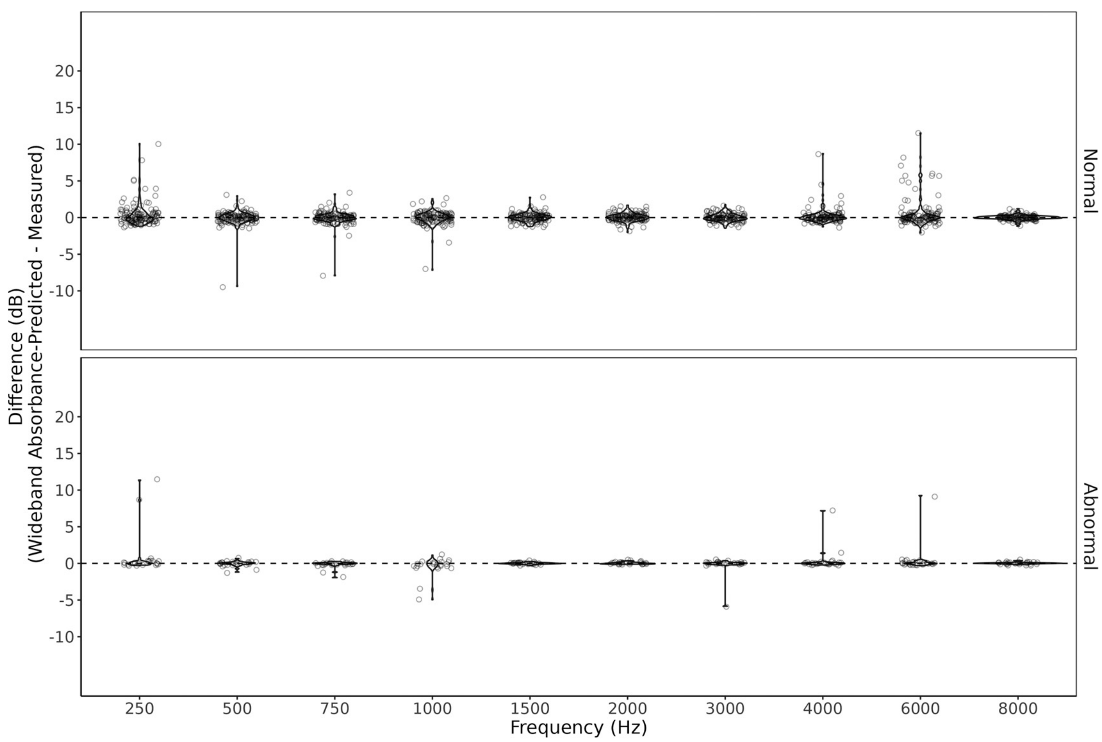

FIG. 3. Violin plots of the difference between the wideband absorbance wRECD model and measured wRECD by frequency and middle-ear status (upper panel, normal middle-ear status; lower panel, abnormal middle-ear status). Circles represent individual differences at each frequency between model predictions and measured wRECD. The violin plot provides a symmetrical representation of the distribution of values at each frequency with the vertical boundaries representing the range of differences.

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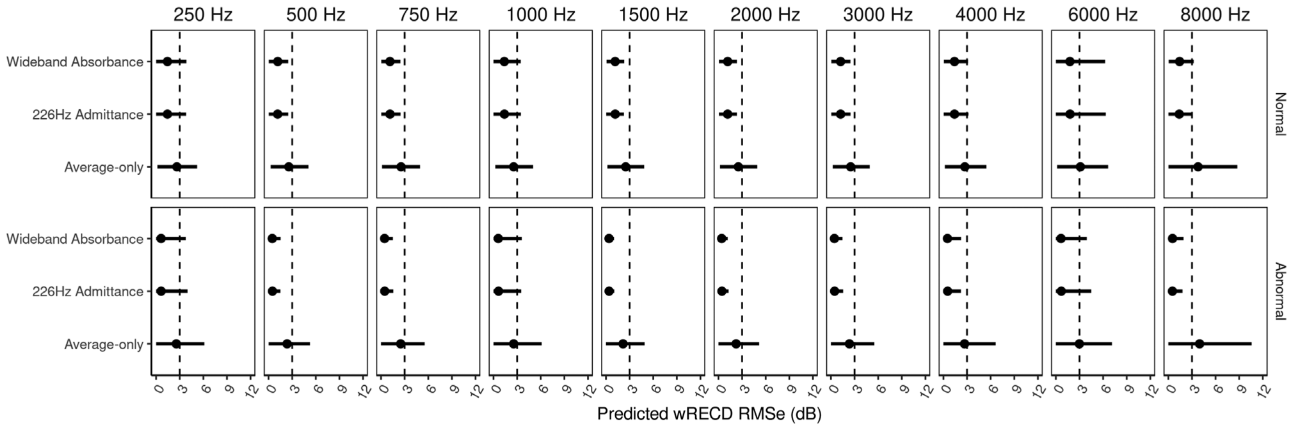

FIG. 4. Comparison of model RMSE by frequency (columns) and middle-ear status (upper panel, normal middle-ear status; lower panel, abnormal middle-ear status). The wideband absorbance, 226 Hz admittance, and average age-based wRECD models are shown within each panel. Points represent median estimates; horizonal bars indicate the 89% highest-density CI around the median estimates.

groups. The RMSEs for the 226 Hz admittance and wideband absorbance wRECD models were smaller than the average age-based wRECD model by approximately 1 dB at 500, 750, 1000, 1500, 2000, and 3000 Hz for both middle-ear status groups.

To further compare the accuracy of the three models for predicting the measured wRECD, we calculated the proportion of cases where each model was within 3 dB of each child's measured wRECD. Figure 5 shows the percentage of cases for each model that were within 3 dB of each child's measured wRECD. For children with normal middle-ear status, the wideband absorbance model had a higher proportion of cases within 3 dB of the measured wRECD at every frequency except 6000 Hz than the average age-based wRECD model. The average age-based wRECD model was within 3 dB in 62.3% (89% CI 60.7%–63.7%) of cases across frequency, whereas the proportion of cases within 3 dB for the wideband absorbance model was 90.1% of cases (89% CI 89.0%–91.4%), and 90.0% of cases (89% CI 88.6%–91.1%) were within 3 dB with the 226 Hz admittance model. A larger proportion of cases had smaller errors by incorporating individual immittance data into predictions of wRECD compared to using an average wRECD. Figure 6 contrasts the average wRECD and wideband absorbance wRECD across age by frequency and middle-ear status.

The conditional effects of age, equivalent ear-canal volume, and absorbance collapsed across frequency from the wideband absorbance model are shown in Fig. 7. There was a negative relationship between wRECD and age, with wRECD values decreasing as age increased. Likewise, wRECD decreased as absorbance and ear-canal volume increased. Absorbance showed the same negative relationship with wRECD in both middle-ear status groups, but the 89% CI was larger for the children with abnormal middle-ear function, indicating greater model uncertainty for children in that group. These trends are consistent with the anticipated relationships between these variables and the wRECD from previous studies (Feigin *et al.*, 1989; Voss and Herrmann, 2005).

IV. DISCUSSION

The goal of this study was to determine whether predictions of individual ear-canal acoustics using an age-based average wRECD could be improved by incorporating clinical middle-ear immittance measures when an individual wRECD cannot be measured. Data extracted from wideband acoustic immittance measurements from 150 children with intact tympanic membranes were used to construct three Bayesian statistical models using measured wRECD: a wideband absorbance wRECD model, a 226 Hz admittance wRECD model, and an age-based average age-based wRECD model. Our hypothesis was that the wideband absorbance wRECD model would provide the most accurate estimates of the child's measured wRECD by characterizing the impedance of the ear at a broader range of frequencies at ambient pressure. The 226 Hz admittance wRECD model was expected to provide more accurate estimates of wRECD than the age-based average age-based wRECD model. However, these expectations were only partially confirmed. Our results suggest that model predictions of wRECD that incorporate individual measures of immittance from either wideband absorbance or 226 Hz tympanometry provide an estimate of wRECD that is within 3 dB of the child's measured RECD in approximately 90% of cases (Fig. 5). In this analysis, the wideband absorbance measures did not improve the accuracy or reduce the uncertainty of model predictions of measured wRECD compared to the 226 Hz admittance model. The age-based average age-based wRECD model produced estimates of measured wRECD that were within 3 dB in approximately 62% of cases. Incorporating individual immittance measures to predict wRECD can improve the accuracy and reduce uncertainty of predictions of the wRECD transform that is used in hearing aid fitting for infants and young children when a child's ear-canal acoustics cannot be directly measured. This approach has the potential to improve the accuracy of hearing aid fittings for infants and young children when immittance data are available, but individual wRECD measures cannot be completed due to limited child cooperation or other factors.

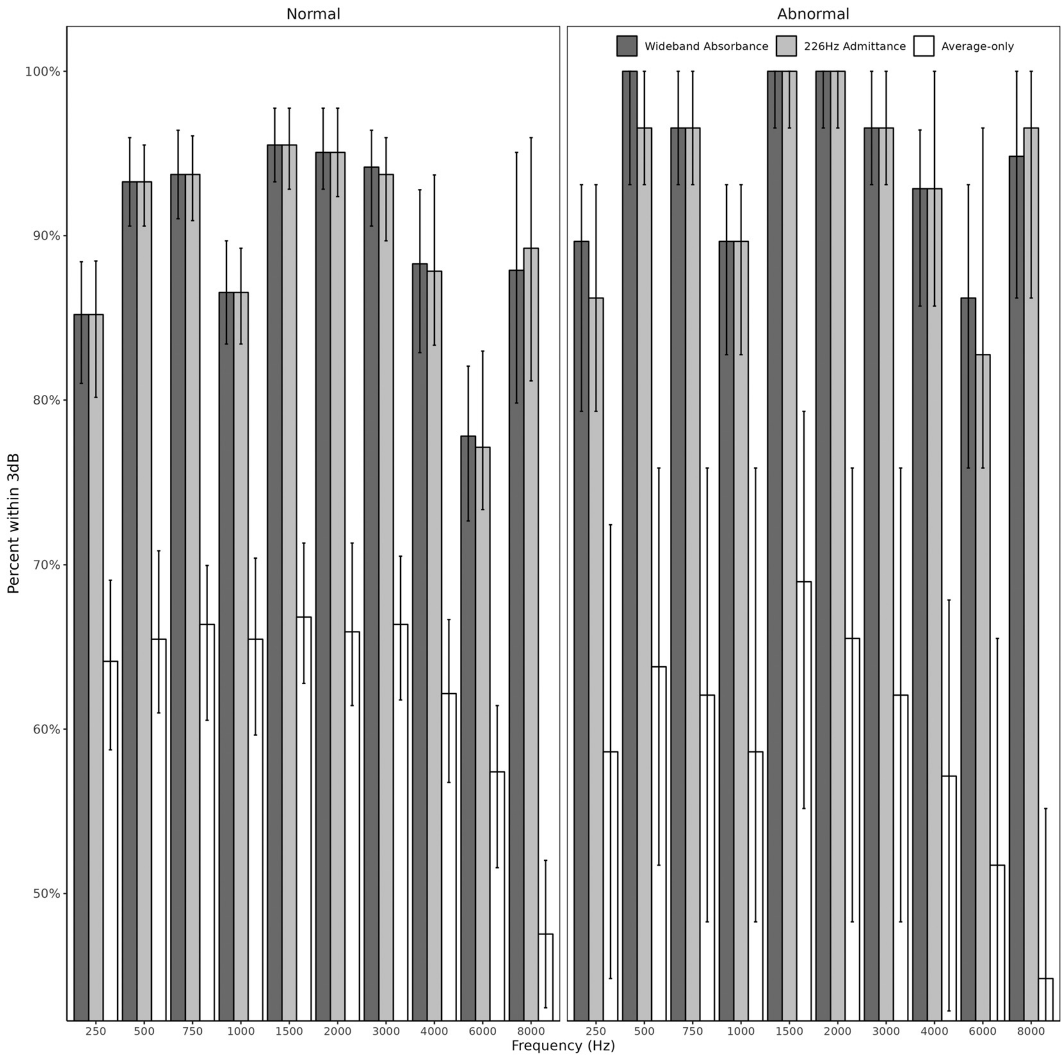

FIG. 5. Bar plots indicating the percentage of cases for each model within 3 dB of the measured wRECD by frequency and middle-ear status (left panel, normal middle-ear status; right panel, abnormal middle-ear status). Dark gray bars represent the wideband absorbance model, light gray bars represent the 226 Hz admittance model, and white bars represent the average wRECD predicted model. The whiskers on each bar represent the 89% CI for model predictions at each frequency.

We hypothesized in this study that using measures of middle-ear absorbance from wideband acoustic immittance could improve predictions of RECD, particularly for wRECD, due to the availability of immittance data across the same broad frequency range of the wRECD compared with the single, low frequency used for 226 Hz tympanometry. Contrary to this prediction, both the 226 Hz admittance wRECD and wideband absorbance wRECD produced similar estimates that were within 3 dB of the child's measured wRECD in 90% of cases regardless of whether the child had normal or abnormal middle-ear function (Fig. 5). For individuals with intact tympanic membranes, the relationship between immittance and ear-canal acoustics appears to be sufficiently predictable based on the limited number of parameters provided by 226 Hz tympanometry.

These findings are consistent with models of ear-canal acoustics that suggest that individual differences in impedance in the coupling of audiometric headphones with the ear canal can produce large individual variation in sound levels in the ear canal up to 35 dB in some cases (Voss *et al.*, 2000a; Voss *et al.*, 2000b; Voss and Herrmann, 2005). The conditional effects of equivalent ear-canal volume and absorbance were consistent with predictions from the previous literature, with decreasing wRECD as ear-canal volume and absorbance increased (Fig. 7). Even characterizing the equivalent volume and impedance of the ear canal and middle-ear system using a 226 Hz probe tone appeared to provide sufficient data to model an accurate representation of ear-canal acoustics for children with intact tympanic membranes. Using absorbance from wideband acoustic immittance to predict the wRECD did not improve predictions compared to 226 Hz admittance, potentially because the predictions of wRECD using the 226 Hz tympanometry and ear-canal volume were already accurate for such a high proportion of cases.

A model using the age-based wRECD to predict the child's measured wRECD produced estimates that were within 3 dB in 62% of cases, which suggests that the current

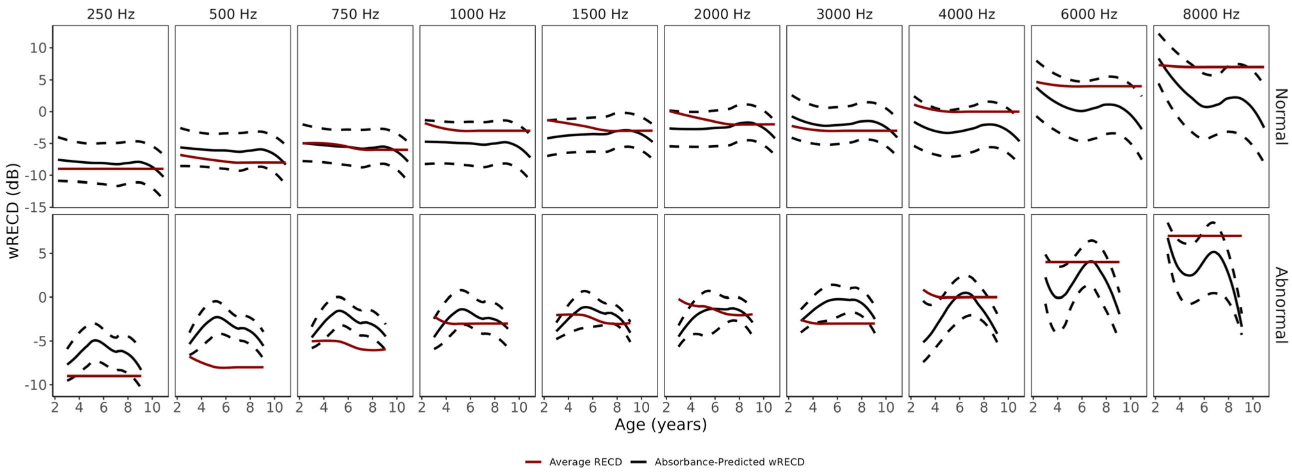

FIG. 6. (Color online) Wideband absorbance wRECD (black line) and average age-based wRECD (red line) as a function of age in years by frequency (columns) and middle-ear status (upper row, normal middle-ear status; lower row, abnormal middle-ear status). The dashed lines in each panel represent the range of the 89% CI for the wideband immittance-predicted wRECD model. The average wRECD and wideband absorbance wRECD model had reasonable concordance of average values between 250 and 3000 Hz, but the average wRECD tended to be higher than the wideband absorbance wRECD from 4000 to 8000 Hz for both middle-ear status groups with a broader range of the 89% CI consistent with greater model uncertainty.

clinical practice of using an age-based average when the RECD or wRECD cannot be measured is still a more accurate approach than relying on predictions from manufacturer hearing aid fitting software or not performing hearing aid verification at all. An examination of hearing aid verification practices and hearing aid fitting outcomes for a large number of children suggested that 55% of children with hearing loss had average fitting errors > 5 dB in at least one ear (McCreery *et al.*, 2015). Further, average fitting errors were approximately ±8 dB for children with hearing loss who were fitted by audiologists who self-reported that they did not conduct electroacoustic verification of the child's hearing aid fitting at all (McCreery *et al.*, 2013). Large fitting errors can lead to reduced audibility, which has been associated with poorer language (Tomblin *et al.*, 2014; Tomblin *et al.*, 2015) and academic (Tomblin *et al.*, 2020) outcomes for children who wear hearing aids. The reasons are unclear as to why coupler-based verifications are not completed, but even in studies with experienced pediatric audiologists and the necessary equipment, RECD can only be successfully

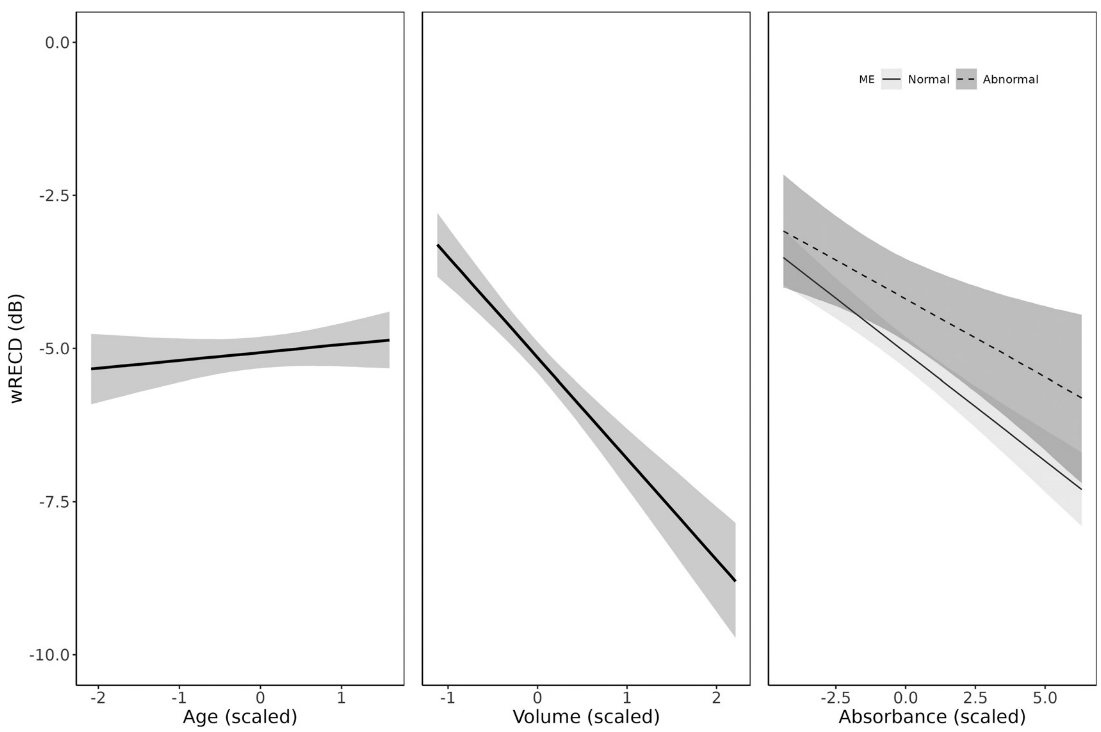

FIG. 7. The conditional effects of age (left panel), equivalent ear-canal volume (middle panel), and absorbance (right panel) on wRECD from the wideband absorbance wRECD model. The solid line represents the average effect of age and equivalent ear-canal volume for all participants and the effect of absorbance for children with normal middle-ear function. The dashed line in the absorbance panel represents the conditional effect of absorbance on RECD for children with abnormal middle-ear function. The shaded area around each line represents the 89% CI around the average from the model.

measured in 60%–70% of cases for infants and young children (McCreery *et al.*, 2015; Bagatto *et al.*, 2016). Recent studies suggest that immittance can be measured in nearly 100% of clinical audiology visits for typically developing infants and young children (Skretta *et al.*, 2022). Thus, a clinical procedure that leverages the models developed here to predict individual RECD or wRECD based on tympanometry or wideband acoustic immittance has the potential to improve hearing aid fitting outcomes for children with hearing loss.

All three models considered in this analysis produced estimates within 3 dB of the child's measured wRECD in a higher proportion of cases than the average RECD and 226 Hz immittance-predicted models from our previous study (McCreery *et al.*, 2023). The previous average-RECD model was within the child's measured RECD for approximately 50% of ears (compared to 62% within 3 dB for the average age-based wRECD model here), and the 226 Hz admittance model was within 3 dB in 71% of ears (compared to 90% within 3 dB for the 226 Hz admittance and wideband absorbance wRECD models). There are several differences in the study procedures and subject populations that could have led to these differences in findings between studies. The previous study was conducted as part of a longitudinal study where data were collected by multiple pediatric audiologists at three clinical sites and using a combination of traditional clinical, laboratory, and mobile data collection sites. These conditions could have led to greater variability in the measured RECD and immittance data used for these models compared to the data for this analysis that were collected by a single examiner in one laboratory using the same equipment for all participants. The data collected by multiple audiologists across different clinical sites could be a more accurate reflection of the precision and variability that would be observed if these models were implemented clinically.

The largest discrepancies and highest uncertainty between measured wRECD and model-predicted wRECD for all three models occurred at frequencies between 4000 and 8000 Hz (Figs. 1 and 3). Greater variability of model predictions at higher frequencies was also observed in our previous study using 226 Hz tympanometry to predict RECD (McCreery *et al.*, 2023). Increased variability in ear-canal measurements at higher frequencies has been well-documented in the literature (Gilman and Dirks, 1986; Chan and Geisler, 1990) and in previous studies that have measured the RECD (Bagatto *et al.*, 2005) and wRECD (Vaisberg *et al.*, 2018). The variability in probe microphone measures in the ear canal has been attributed to acoustic standing waves in the ear canal from reflected energy from the tympanic membrane or other surfaces in the ear canal (Siegel, 1994). At the position of the probe microphone in the ear canal, acoustic reflections lead to frequency-specific variation in measurements of ear-canal dB SPL that reduce reliability (McCreery *et al.*, 2009). Alternatives to characterizing dB SPL in the ear canal have been developed that use source and load impedance of the transducer and ear canal to estimate incident sound levels without contamination from reflections, including estimating dB forward pressure level (dB FPL; Neely and Gorga, 2010) or dB integrated pressure level (dB IPL; Lewis *et al.*, 2009). These approaches have shown promising results in laboratory studies for minimizing artifacts from acoustic reflections in ear-canal sound level measurements for otoacoustic emissions (Scheperle *et al.*, 2008), probe microphone measures for hearing aid verification (McCreery *et al.*, 2009), and audiometric measures calibrated to the ear canal (Lapsley-Miller *et al.*, 2018). Future research should determine whether immittance-predicted wRECD measures referenced to dB FPL or dB IPL could provide better estimates with a smaller range of uncertainty than wRECD measures referenced in dB SPL in the ear canal.

The presence of tympanostomy tubes and tympanic membrane perforation has a significant impact on the RECD related to substantial changes in impedance that occur with these conditions (Voss and Herrmann, 2005). Nearly 15% of children with hearing loss in one previous study had at least one visit where their tympanic membrane was not intact (McCreery *et al.*, 2015). The RECD for a child with a tympanostomy tube or perforation of the tympanic membrane can be 20 dB lower than the average RECD values, particularly at frequencies $<$1000 Hz. At present, this difference precludes the use of average RECD values for children with tympanostomy tubes or perforations and creates potential for substantial inaccuracies when such results are applied to predict the output of a hearing aid in the child's ear canal when the RECD or wRECD cannot be measured directly. Although all the children in this analysis and our previous study (McCreery *et al.*, 2023) had intact tympanic membranes, future studies should apply these concepts to develop RECD and wRECD predictions of children with non-intact tympanic membranes.

In conclusion, we used clinical measures of immittance, including 226 Hz tympanometry and wideband acoustic immittance absorbance, to develop statistical models to predict the wRECD in a large group of children to improve hearing aid verification outcomes when the individual wRECD cannot be measured. Compared to a model using the age-based average wRECD, both 226 Hz admittance and wideband absorbance wRECD models produced estimates of a child's measured wRECD that were within 3 dB in 90% of cases. These results highlight the potential for improving the hearing aid fitting process for infants and young children by incorporating individual measures of middle-ear immittance from widely available clinical measures. Development of a clinical implementation of these models for further validation by audiologists is a logical next step to determine whether these models can be replicated in a clinical context and produce improved hearing aid fitting outcomes.

ACKNOWLEDGMENTS

Research reported in this publication was entirely supported by the National Institute on Deafness and other Communication Disorders of the National Institutes of Health under Award Nos. R01 DC013591, R01 DC018330, and T35 DC008757, as well as by the National Institute for General Medical Sciences under Award No. P20GM109023. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Alaerts, J., Luts, H., and Wouters, J. (**2007**). "Evaluation of middle ear function in young children: Clinical guidelines for the use of 226- and 1,000-Hz tympanometry," Otol. Neurotol. **28**(6), 727–732.

Bagatto, M., Moodie, S., Brown, C., Malandrino, A., Richert, F., Clench, D., and Scollie, S. (**2016**). "Prescribing and verifying hearing aids applying the American Academy of Audiology pediatric amplification guideline: Protocols and outcomes from the Ontario infant hearing program," J. Am. Acad. Audiol. **27**(3), 188–203.

Bagatto, M., Moodie, S., Scollie, S., Seewald, R., Moodie, S., Pumford, J., and Liu, K. R. (**2005**). "Clinical protocols for hearing instrument fitting in the Desired Sensation Level method," Trends Amplif. **9**(4), 199–226.

Bagatto, M. P., Scollie, S. D., Seewald, R. C., Moodie, K. S., and Hoover, B. M. (**2002**). "Real-ear-to-coupler difference predictions as a function of age for two coupling procedures," J. Am. Acad. Audiol. **13**(8), 407–415.

Blumsack, J. T., Clark-Lewis, S., Watts, K. M., Wilson, M. W., Ross, M. E., Soles, L., and Ennis, C. (**2014**). "Alternative metrics for real-ear-to-coupler difference average values in children," J. Am. Acad. Audiol. **25**(9), 823–833.

Bürkner, P. C. (**2017**). "brms: An R package for Bayesian multilevel models using Stan," J. Stat. Softw. **80**(1), 1–28.

Carpenter, B., Gelman, A., Hoffman, M. D., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P., and Riddell, A. (**2017**). "Stan: A probabilistic programming language," J. Stat. Softs. **76**, 1–32.

Chan, J. C., and Geisler, C. D. (**1990**). "Estimation of eardrum acoustic pressure and of ear canal length from remote points in the canal," J. Acoust. Soc. Am. **87**(3), 1237–1247.

Cox, R. M., and Alexander, G. C. (**1990**). "Evaluation of an in-situ output probe-microphone method for hearing aid fitting verification," Ear Hear. **11**(1), 31–39.

Feigin, J. A., Kopun, J. G., Stelmachowicz, P. G., and Gorga, M. P. (**1989**). "Probe tube microphone measures of ear-canal sound pressure levels in infants and children," Ear Hear. **10**(4), 254–258.

Gabry, J., and Češnovar, R. (**2021**). "CmdStanR: R interface to 'CmdStan,'" https://mc-stan.org/cmdstanr (Last viewed December 16, 2021).

Gilman, S., and Dirks, D. D. (**1986**). "Acoustics of ear canal measurement of eardrum SPL in simulators," J. Acoust. Soc. Am. **80**(3), 783–793.

Groon, K. A., Rasetshwane, D. M., Kopun, J. G., Gorga, M. P., and Neely, S. T. (**2015**). "Air-leak effects on ear-canal acoustic absorbance," Ear Hear. **36**, 155–163.

Halpin, K. S., Smith, K. Y., Widen, J. E., and Chertoff, M. E. (**2010**). "Effects of universal newborn hearing screening on an early intervention program for children with hearing loss, birth to 3 yr of age," J. Am. Acad. Audiol. **21**(3), 169–175.

Holte, L., Walker, E., Oleson, J., Spratford, M., Moeller, M. P., Roush, P., Ou, H., and Tomblin, J. B. (**2012**). "Factors influencing follow-up to newborn hearing screening for infants who are hard-of-hearing," Am. J. Audiol. **21**(2), 163–174.

Hunter, L. L., Prieve, B. A., Kei, J., and Sanford, C. A. (**2013**). "Pediatric applications of wideband acoustic immittance measures," Ear Hear. **34**, 36s–42s.

International Electrotechnical Commission (IEC) (**2006**). "Electroacoustics—Simulators of human head and ear—Part 5: 2 cm^3 coupler for the measurement of hearing aids and earphones coupled to the ear by means of ear inserts," IEC International Standard 60318-5 (IEC, Geneva, Switzerland).

Lapsley-Miller, J. A., Reed, C. M., Robinson, S. R., and Perez, Z. D. (**2018**). "Pure-tone audiometry with forward pressure level calibration leads to clinically-relevant improvements in test–retest reliability," Ear Hear. **39**(5), 946–957.

Lewis, J. D., McCreery, R. W., Neely, S. T., and Stelmachowicz, P. G. (**2009**). "Comparison of *in-situ* calibration methods for quantifying input to the middle ear," J. Acoust. Soc. Am. **126**(6), 3114–3124.

Martin, H. C., Munro, K. J., and Lam, M. C. (**2001**). "Perforation of the tympanic membrane and its effect on the real-ear-to-coupler difference acoustic transform function," Br. J. Audiol. **35**(4), 259–264.

Martin, H. C., Munro, K. J., and Langer, D. H. (**1997**). "Real-ear to coupler differences in children with grommets," Br. J. Audiol. **31**(1), 63–69.

Martin, H. C., Westwood, G. F. S., and Bamford, J. M. (**1996**). "Real ear to coupler differences in children having otitis media with effusion," Br. J. Audiol. **30**(2), 71–78.

McCreery, R. W., Bentler, R. A., and Roush, P. A. (**2013**). "Characteristics of hearing aid fittings in infants and young children," Ear Hear. **34**(6), 701–710.

McCreery, R. W., Crukley, J., Grindle, A., Merchant, G. R., and Walker, E. W. (**2023**). "Predicting children's real-ear-to-coupler differences based on tympanometric data," Int. J. Audiol. **62**(5), 462–471.

McCreery, R. W., Pittman, A., Lewis, J., Neely, S. T., and Stelmachowicz, P. G. (**2009**). "Use of forward pressure level to minimize the influence of acoustic standing waves during probe-microphone hearing-aid verification," J. Acoust. Soc. Am. **126**(1), 15–24.

McCreery, R. W., Walker, E. A., Spratford, M., Bentler, R., Holte, L., Roush, P., Oleson, J., Van Buren, J., and Moeller, M. P. (**2015**). "Longitudinal predictors of aided speech audibility in infants and children," Ear Hear. **36**, 24S–37S.

Moeller, M. P., and Tomblin, J. B. (**2015**). "An introduction to the outcomes of children with hearing loss study," Ear Hear. **36**(Suppl. 1), 4S–13S.

Moodie, K. S., Seewald, R. C., and Sinclair, S. T. (**1994**). "Procedure for predicting real-ear hearing aid performance in young children," Am. J. Audiol. **3**(1), 23–31.

Munro, K. J., and Buttfield, L. M. (**2005**). "Comparison of real-ear to coupler difference values in the right and left ear of adults using three earmold configurations," Ear Hear. **26**(3), 290–298.

Neely, S. T., and Gorga, M. P. (**2010**). "Forward-pressure level for in-the-ear calibration," J. Acoust. Soc. Am. **127**(3), 1868.

Nelson-Barlow, N., Auslander, M., Rines, D., and Stelmachowicz, P. G. (**1988**). "Probe microphone measures in hearing impaired children and adults," Ear Hear. **9**(5), 243–247.

R Core Team (**2022**). *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, Vienna, Austria).

Scheperle, R. A., Neely, S. T., Kopun, J. G., and Gorga, M. P. (**2008**). "Influence of *in situ*, sound-level calibration on distortion-product otoacoustic emission variability," J. Acoust. Soc. Am. **124**(1), 288–300.

Siegel, J. H. (**1994**). "Ear-canal standing waves and high-frequency sound calibration using otoacoustic emission probes," J. Acoust. Soc. Am. **95**(5), 2589–2597.

Skretta, D., Al-Salim, S. A., and Merchant, G. R. (**2022**). "Limited audiological assessment results in children with otitis media with effusion," in *Proceedings of the Nebraska Speech-Language-Hearing Association Annual Convention*, October 14–15, Lincoln, NE (Nebraska Speech-Language-Hearing Association, Lincoln, NE).

Tomblin, J. B., Harrison, M., Ambrose, S. E., Walker, E. A., Oleson, J. J., and Moeller, M. P. (**2015**). "Language outcomes in young children with mild to severe hearing loss," Ear Hear. **36**, 76S–91S.

Tomblin, J. B., Oleson, J., Ambrose, S. E., Walker, E. A., McCreery, R. W., and Moeller, M. P. (**2020**). "Aided hearing moderates the academic outcomes of children with mild to severe hearing loss," Ear Hear. **41**(4), 775–789.

Tomblin, J. B., Oleson, J. J., Ambrose, S. E., Walker, E., and Moeller, M. P. (**2014**). "The influence of hearing aids on the speech and language development of children with hearing loss," J. Otolaryngol. Head Neck Surg. **140**(5), 403–409.

Vaisberg, J. M., Folkeard, P., Pumford, J., Narten, P., and Scollie, S. (**2018**). "Evaluation of the repeatability and accuracy of the wideband real-ear-to-coupler difference," J. Am. Acad. Audiol. **29**(6), 520–532.

Van Eeckhoutte, M., Scollie, S., O'Hagan, R., and Glista, D. (**2020**). "Perceptual benefits of extended bandwidth hearing aids with children: A within-subject design using clinically available hearing aids," J. Speech Lang. Hear. Res. **63**(11), 3834–3846.

Vehtari, A., Gelman, A., and Gabry, J. (**2017**). "Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC," Stat. Comput. **27**, 1413–1432.

Voss, S. E., and Herrmann, B. S. (**2005**). "How does the sound pressure generated by circumaural, supra-aural, and insert earphones differ for adult and infant ears?" Ear Hear. **26**(6), 636–650.

Voss, S. E., Rosowski, J. J., Merchant, S. N., Thornton, A. R., Shera, C. A., and Peake, W. T. (**2000a**). "Middle ear pathology can affect the ear canal sound pressure generated by audiologic earphones," Ear Hear. **21**(4), 265–274.

Voss, S. E., Rosowski, J. J., Shera, C. A., and Peake, W. T. (**2000b**). "Acoustic mechanisms that determine the ear-canal sound pressures generated by earphones," J. Acoust. Soc. Am. **107**(3), 1548–1565.

Watts, K. M., Bagatto, M., Clark-Lewis, S., Henderson, S., Scollie, S., and Blumsack, J. (**2020**). "Relationship of head circumference and age in the prediction of the real-ear-to-coupler difference (RECD)," J. Am. Acad. Audiol. **31**(7), 496–505.

Zwislocki, J. (**1962**). "Analysis of the middle-ear function. Part I: Input impedance," J. Acoust. Soc. Am. **34**(9B), 1514–1523.