Published in final edited form as:

Hear Res. 2017 February ; 344: 62–67. doi:10.1016/j.heares.2016.10.029.

Maturation of middle ear transmission in children

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Abstract

The goal of the current study was to characterize the normative features of wideband acoustic immittance in children for describing the functional maturation of the middle ear in 5 to 12-year-old children. Absorbance and group delay were measured in adults and three groups of children, 5–6, 7–9 and 10–12-year-olds, in a cross-sectional design. Absorbance showed significant effects of the age group in four out of ten center frequencies of one-half-octave bins from 211 to 6000 Hz, while there was no significant effect for group delay at any frequency. Older children (10–12 years) showed absorbance similar to adults. Test-retest reliability was high for absorbance for all age groups. However, group delay was modestly reliable only for adults. We conclude that the middle ear transmission follows a protracted period of maturation for high frequencies and reaches adult-like feature by 10 to 12 years of age.

Keywords

absorbance; group delay; middle ear transmission; wideband acoustic immittance

1. INTRODUCTION

Most auditory experiments and audiologic tests are dependent on sound conduction through the middle ear. Sound transmission through the middle ear undergoes developmental changes throughout infancy (Hunter et al., 2015; Keefe and Levi, 1996; Keefe et al., 1993; Sanford and Feeney, 2008; Werner et al., 2010) and continues into childhood (Beers et al., 2010; Hunter et al., 2008; Okabe et al., 1988; Wang et al., 2016). Maturation of the middle ear transmission has important implications for perceptual and physiologic studies of auditory development.

Wideband acoustic immittance (WAI) has emerged as a powerful tool to probe middle ear function across the human life span and for the diagnosis of middle ear disorders (Feeney et al., 2013). WAI refers to a group of tests that include acoustical variables such as

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reflectance, absorbance, and the underlying phase and magnitude expressed in terms of admittance or impedance (Rosowski et al., 2013). WAI may be obtained over a broad frequency range using transient stimuli such as clicks or chirps, and thus, may be analyzed over a range of frequencies similar to an audiogram. WAI tests can be conducted at ambient pressure without obtaining a hermetic seal, or with pressurization similar to tympanometry. WAI provides functional information regarding how the middle ear receives, absorbs and transmits sound energy across a range of frequencies (Hunter et al., 2013). Among all WAI measures, energy reflectance is commonly studied. The energy reflectance is the ratio of reflected sound energy from the middle ear to incident sound energy at the ear tip (Voss and Allen, 1994). In contrast, absorbance is the ratio of absorbed to incident power, with the assumption that the sound energy in the ear canal is primarily absorbed by the middle ear at the tympanic membrane. Mathematically, absorbance is equal to one minus the energy reflectance. Absorbance ranges from 0 to 1, with 0 meaning that the ear absorbs minimal power or all the power is reflected at the tympanic membrane, and 1 signifying that the middle ear absorbs maximum power from the forward-traveling sound in the ear canal (Liu et al., 2008). Absorbance is relatively independent of the location of the probe within the ear canal compared to admittance (Voss et al., 2008).

Studies that investigated maturational effects in WAI reported ambient energy reflectance, or absorbance, in infants and toddlers of different age groups in cross-sectional (Aithal et al., 2014; Hunter et al., 2008; Keefe et al., 1993; Sanford and Feeney, 2008; Werner et al., 2010) and longitudinal designs (Hunter et al., 2015; Shahnaz et al., 2014). Hunter et al. (2015) characterized tympanometric absorbance and reflectance group delay at tympanometric peak pressure, -300 daPa and 200 daPa, in addition to measuring ambient absorbance. Overall, these studies demonstrated that the mean absorbance is higher in neonates and young infants up to 6 months of age compared to young adults across the frequency range. Among infants, one-month-old infants showed higher absorbance compared to newborns and older infants (Hunter et al., 2015). The high absorbance in frequencies below 1000 Hz in young infants is conjectured to be due to power loss from flaccid ear canal movement (Keefe et al., 1993). In full-term newborns, the absorbance peak is slightly below 2000 Hz, whereas the absorbance has a broad maximum in the 2000 to 4000 Hz frequency region for adults. The shape of the absorbance $\times$ frequency function plot is relatively flat at birth and changes to a peaked pattern more similar to adults by 6 months of age (Hunter et al., 2015).

Clearly, considerable effort has been made for probing the maturation of middle ear transmission via WAI measures in infants and toddlers. In contrast, the developmental effects in WAI for children can be inferred from a few studies (Beers et al., 2010; Hunter et al., 2008; Keefe et al., 2012). Here, we review the normative features from these investigations even though they also examined the efficiency of WAI for assessing middle ear disorders. Hunter et al. (2008) studied ambient reflectance and absorbance for normal and poor status ears in infants and children from 3 days to 47 months of age (below 6 months of age, $n = 33$; 6 to 47 months of age, $n = 64$). Their results showed no significant age effect for reflectance except at 6000 Hz, and no significant effect of stimulus type (sine wave versus broadband chirp), ear, or sex. Beers et al. (2010) reported energy reflectance in 78 children (mean age = 6.15 years; Experiment 1) and compared their pediatric data with the normative data in adults obtained from a previous study (Shahnaz and Bork, 2006). They

found significantly lower energy reflectance in children compared to adults between 2500 and 5000 Hz. Additionally, Caucasian children showed significantly higher reflectance compared to Caucasian adults between 315 and 1250 Hz. This suggests that the pediatric middle ear has a higher sound absorbance at high frequencies, whereas the adult ear has a higher sound absorbance at low frequencies. Another interpretation could be that the ear canal effects are not complete by 6 years of age. Keefe et al. (2012) measured absorbance in 26 children (mean age = 5.5 years). Because of the difference in study goals, Hunter et al., (2008) and Keefe et al., (2012) did not include adult control groups, thus, limiting the ability for making a quantitative comparison between adults and children.

To sum, the middle ear transmission in children remains immature at 6 years of age. The timeline for complete maturation of WAI measures is currently not known. This knowledge would be appealing for both clinicians and researchers alike. For example, it is important to distinguish between variations in middle-ear measurements attributable to developmental changes and those due to middle-ear pathology, or treatment. Knowing the normative features of middle ear transmission in children is important for pediatric hearing aid fittings, for construing hearing experiments in children, and for designing ear simulators.

The goals of this study were to describe the functional maturation of the middle ear as measured by WAI in 5 to 12 years old children and to examine the repeatability of WAI measures parameterized in terms of absorbance and group delay in these children.

2. METHODS

2.1 Subjects

Data from 110 children and 45 adults are reported in this study. Children were studied in three groups using a cross-sectional design: 5–6, 7–9 and 10–12 years. Mean age and sex distribution (M = male and F = female) for each age group were as follows: 5–6 years: 5.52 years, 12 M and 14 F; 7–9 years: 8 years, 16 M and 21 F; 10–12 years: 11.11 years, 21 M and 26 F. Adult subjects (15 M and 30 F) aged between 21 and 35 years (mean = 24.98 years).

All subjects had (1) good general health and no evidence of a developmental disorder, (2) normal ear canal and tympanic membrane as revealed by otoscopic examination, (3) air conduction thresholds ≤ 15 dB HL at octave frequencies from 250 to 8000 Hz and air-bone difference ≤ 10 dB, (4) normal 226 Hz-tympanograms, defined by the peak compensated static acoustic admittance between 0.35 and 1.75 mmho and the tympanometric peak pressure between 50 to -100 daPa (Jerger, 1970), and (5) clinically normal transient evoked otoacoustic emissions with a signal to noise ratio (SNR) of at least 3 dB (Robinette, 2003). All testing was conducted in a double-walled sound-attenuating booth.

2.2 Wideband acoustic immittance measures

WAI at ambient pressure was measured using the HearID+MEPA3 system (Mimosa Acoustics, Champaign, IL) via the MEPA3 software (Version 4.5.0.10) with an ER-10C probe microphone system (Etymotic Research, Elk Grove Village, IL). Measurement of reflectance is defined in Equation 1 (Voss and Allen, 1994).

$$\text{Power reflectance} = |R(f)|^2 \quad (1)$$

Where $R(f) = (Z_{ec}[f] - Z_0) / (Z_{ec}[f] + Z_0)$; Z_{ec} is the ear canal impedance and Z_0 is its characteristic impedance, $Z_0 = \rho c / S$; and ρ is the density of air, c is the speed of sound, and S is the cross-sectional area of the ear canal in the plane of measurement. The Mimosa system physically estimates S based on the diameter of the ear tip selected for measurement. Two different foam ear tips were used for this study: ER10C-14A (13 mm) and 14B (10 mm). Although ambient WAI measurements do not require a hermetic seal in the ear canal, the ear tip that provided a snug seal was used to avoid acoustic leaks. The system was calibrated following the procedure described by Voss and Allen (1994). Briefly, the chirp stimulus was calibrated using an analysis of frequency response and time delay in a set of four hard-walled cavities of different depths. The Thévenin equivalent parameters, source pressure, and impedance were measured from the complex pressure response of these cavities.

WAI measurements were repeated in the same test session at least twice after probe removal and reinsertion in every subject. Prior to making WAI measurements, an in-the-ear calibration was performed to confirm the level of chirp stimuli. This is different from the probe calibration described earlier that is conducted with the calibration cavity set. Wideband chirps at 60 dB SPL (rms) were presented in the ear canal for 100 s (or shorter if the SNR was > 20 dB), time averaged, and analyzed from 211 to 6000 Hz with 23-Hz intervals (i.e., a total of 248 frequencies). This measurement from the subject's ear canal and the related Thévenin equivalent parameters obtained during the calibration process were used to compute the pressure frequency response and power reflectance (Voss and Allen, 1994). Power reflectance ($|R|^2$, stated in Equation 1) is defined as the percentage of reflected power to incident power. Power absorbance, or simply absorbance, was computed using the power reflectance. Reflectance group delay (expressed in μ s) is the negative of the derivative (slope) of the pressure reflectance phase as a function of frequency, divided by a factor of 2π .

2.3 Statistical procedures

The experimental questions were answered by analyzing absorbance and group delay. Shapiro-Wilk tests of normality determined the probability distribution of the measures at one-half-octave bins with center frequencies 250, 354, 500, 707, 1000, 1414, 2000, 2828, 4000 and 5656 Hz. Descriptive statistics such as the mean, and 5th and 95th percentiles were computed for all 248 frequencies, from 211 to 6000 Hz, while 95% confidence intervals of the mean were computed at center frequencies for the four age groups. Repeated measures analysis of variance (ANOVA), with center frequency as the within-subjects factor and age group as the between-subjects factor, examined the effects of frequency, age group, and their interaction. The Greenhouse–Geisser adjustment was applied to correct for the violation of compound symmetry and sphericity assumptions when the result was statistically significant on Mauchly's test. False discovery rate (FDR) procedures were used for multiple comparisons based on *t*-tests (Benjamini and Hochberg, 1995). The relative reliability or

internal consistency of absorbance and group delay was quantified using Cronbach's α for each age group and center frequency. The following rules were applied for interpreting Cronbach's α : 0.9 = excellent, 0.8 = good, 0.7 = acceptable, 0.6 = questionable, 0.5 = poor, and < 0.5 = unacceptable (George and Mallery, 2003). The significance level for statistical tests was set at 0.05.

3. RESULTS

3.1 Absorbance

The mean absorbance as a function of frequency for the four age groups is plotted in Figure 1. The curves joining the means for all age groups show a similar configuration with the absorbance at a minimum at 250 Hz, gradually increasing with frequency achieving a broad maximum between 2828 and 4000 Hz, and then sharply decreasing at 5656 Hz. Note that these frequencies are center frequencies of one-half-octave bins. Figure 2 depicts the mean and percentiles (5th and 95th) of absorbance at 248 frequencies for the three age groups of children with equivalent adult normative data. The percentiles demonstrate similar absorbance-frequency functions as observed in Figure 1 across age groups. The 95th percentile approached an absorbance of 1 at around 3000 Hz for 5–6 and 7–9-year-olds. Similarly, the 5th percentile approached an absorbance of 0 in the low frequencies around 211 to 350 Hz for the children age groups.

ANOVA revealed a significant main effect for frequency ($F_{3,20, 342.27} = 422.36, p < 0.001, \eta_p^2 = 0.80$) and a significant interaction effect between frequency and age group ($F_{9,60, 342.27} = 2.00, p = 0.04, \eta_p^2 = 0.05$). However, the main effect for age group was not significant ($F_{3, 107} = 0.54, p = 0.66, \eta_p^2 = 0.02$). Table 1 presents the significant results from post-hoc analysis using FDR. Significant group differences were found at 500, 2000, 2828 and 4000 Hz. Figure 3 shows the mean absorbance across age groups for these frequencies and demonstrates the developmental trend. The absorbance at 500 Hz was significantly lower in 5–6 and 7–9-year-olds compared to adults and 10–12-year-olds. At 2000 Hz, the absorbance in 5–6-year-olds was significantly higher compared to adults and 10–12-year-olds. For 2828 Hz, the absorbance was significantly higher in 5–6 and 7–9-year-olds relative to adults; however only 5–6-year-olds had significantly higher absorbance compared to 10–12-year-olds. The absorbance at 4000 Hz in 5–6 and 7–9-year-olds was significantly higher compared to adults and 10–12-year-olds.

Hierarchical multiple regression analyses were conducted, for frequencies where significant developmental effects were obtained (i.e., 500, 2000, 2828 and 4000 Hz), to determine whether the middle ear pressure (measured via the tympanometric peak pressure) contributed incrementally to the prediction of absorbance above and beyond that accounted for by age. Age was entered as block 1, and middle ear pressure was entered as block 2. For 500 Hz, analysis revealed that age did not contribute significantly to the regression model ($F_{1, 57} = 1.06, p = 0.31$). Introducing middle ear pressure explained 25% of the variance in absorbance ($R^2 = 0.23, F_{2, 56} = 9.21, p < 0.001; \beta = 0.49, p < 0.001$). Similar results were found for 2000 Hz (Age: $F_{1, 62} = 3.24, p = 0.08$; middle ear pressure: $R^2 = 0.10, F_{2, 61} = 5.43, p = 0.01; \beta = 0.49, p = 0.01$). Results were not significant for 2828 and 4000 Hz ($p > 0.05$).

Cronbach's α for absorbance for all center frequencies across age groups are reported in Table 2. Overall, the reliability of absorbance for all age groups ranged from *acceptable* to *excellent* across all frequencies, but 250 Hz which was *questionable* for 5–6 and 10–12-year-olds.

3.2 Group delay

The mean group delay across frequencies for all age groups is shown in Figure 4. The four age groups show a similar characteristic trend: the group delay decreases with frequency, reaching a minimum around 1000 to 1414 Hz, then increases to reach a maximum between 2828 and 4000 Hz. ANOVA showed a significant main effect for frequency ($F_{7.46, 782.99} = 3.23, p = 0.002, \eta_p^2 = 0.03$); however, no significant effect for age group ($F_{3, 105} = 0.09, p = 0.97, \eta_p^2 = 0.002$), or age group and frequency interaction ($F_{22.37, 782.99} = 0.93, p = 0.002, \eta_p^2 = 0.03$). The reliability for group delay ranged from *unacceptable* to *questionable* depending on the frequency and age group, except at 1000 Hz where it was *acceptable* for adults (Table 2).

4. DISCUSSION

Despite more than two decades of research on WAI, the timeline for functional maturation of the middle ear in children has not previously been reported. This is a critical gap in knowledge and it is important to bridge this knowledge gap for several reasons described in the Introduction (section 1). The present study investigated the characteristics of absorbance and group delay in 5 to 12-year-old children using a cross-sectional design to determine the maturation of middle ear transmission with age. A longitudinal design might provide more specifics of the growth pattern, but will take at least seven years to complete the study and thus may be practically difficult to conduct. The main finding of the present study suggests that the middle ear transmission, as measured by WAI, continues to mature in children aged 5 through 9 years, and achieves adult-like features by 10 to 12 years of age.

4.1 Timeline for developmental changes

Previous work collectively suggests that WAI measures undergo a series of developmental changes from birth through 6 years (Aithal et al., 2014; Hunter et al., 2015, 2008; Keefe et al., 1993; Sanford and Feeney, 2008; Shahnaz et al., 2014; Werner et al., 2010). The current study showed developmental changes in absorbance for four frequency regions (center frequencies of one-half-octave bins: 500, 2000, 2828 and 4000 Hz), while other frequency regions (250, 354, 707, 1000, 1414 and 5656 Hz) were adult-like in the youngest age group (5 to 6 years). We also found that different frequencies follow different maturational timelines and change patterns (increase vs. decrease) in absorbance.

The absorbance–frequency function for all children age groups had a broad maximum between 2000 and 4000 Hz similar to adults, consistent with the literature that shows adult-like shape by 6 months of age (e.g., Hunter et al., 2015). Absorbance increased only at 500 Hz with age to attain adult-like value by 10 to 12 years, suggesting that the children's (5 to 9 years) middle ear absorbs less power at low frequencies compared to adults and older children (10–12 years). This interpretation is consistent with Beers et al. (2010) who

reported significantly higher reflectance for Caucasian children aged 5 to 6 years relative to Caucasian adults, for a broader frequency region from 315 to 1250 Hz.

The absorbance at 2000 Hz in children decreased with age and reached adult values by 7 to 9 years of age, whereas for 2828 and 4000 Hz, absorbance was adult-like only by 10 to 12 years. This implies that absorbance matures from lower to higher frequencies among high frequencies and that the pediatric middle ear (5 to 9 years) absorbs more sound at high frequencies compared to adults and older children (10–12 years). Although Beers et al. (2010) reported similar findings in 5 to 6-year-olds (i.e., lower reflectance relative to adults at high frequencies: 2500–5000 Hz), their study does not provide information regarding the age at which reflectance becomes adult-like. Likewise, Hunter et al. (2008) showed significant developmental effects for children (3 days through 4 years) only at the highest frequency tested (6000 Hz). To sum, absorbance matures by 10 to 12 years of age for all frequencies (where significant results were observed) but 2000 Hz, where it becomes adult-like by 7 to 9 years.

Two potential confounds, middle ear pressure, and the measurement method, are worth some consideration. Although the general status of the middle ear was confirmed by tympanometry and pure-tone air-bone difference, the middle ear pressure was not balanced between the groups. In general, children tend to have more negative middle ear pressure than adults (Margolis and Heller, 1987; Smyth, 1977). The middle ear pressure predicted absorbance for 500 and 2000 Hz, suggesting that the middle ear pressure may mechanistically explain some of the developmental trends observed in this study. Shaver and Sun (2013) showed that induced negative middle ear pressure could increase the reflectance at frequencies below 2000 Hz and decrease at frequencies above approximately 3000 Hz. The absorbance for the children in the 5–6 and 7–9-year-old age groups showed this pattern compared to adults. However, a big question is whether the induced negative middle ear pressure (i.e., a change from the baseline) in adults is a good model for the normal, negative middle ear pressure in children. The Eustachian tube is typically collapsed in children due to less cartilage. In addition, the cartilage is more compliant and the tensor veli palatini muscle functions less effectively in children compared to adults (Kitajiri et al., 1987; Silman and Silverman, 1996). As a result, the middle ear pressure is relatively negative, which is a natural phenomenon for children.

The second factor is related to the method with which the Mimosa system determines the ear canal cross-sectional area, which is related to the foam eartip size. The ER10C-14A and 14B foam eartips have an area of about 154 mm² and 79 mm² respectively. These are both large in comparison to the ear canal cross-sectional areas estimated by Keefe and Abdala, (2007; 58 mm²) and by Voss et al., (2008; 49 mm²) in adults. It is likely that the size differential between the large tip size and the smaller ear canal cross-sectional area would be greater for younger children and may decrease with age, although a description of the ear canal cross-sectional area for school-aged children is currently lacking. This could lead to lower absorbance in the low frequencies below approximately 2000 Hz and higher absorbance in the high frequencies above approximately 3000 Hz for the younger children, according to the data of Keefe et al. (1993; their Figure A1), which shows the change in energy reflectance when the estimate of the ear canal cross-sectional area is increased by 20%.

Therefore, it is cautioned that the developmental trend of increasing absorbance in the low frequencies and decreasing absorbance in the high frequencies with age observed in this study should be interpreted in light of this potential measurement confound—ear canal cross-sectional area estimation approach.

In contrast to absorbance, group delay results do not share the same developmental trends. Group delay signifies the time elapsed since the stimulus leaves the probe transducer, travels to the tympanic membrane, and is reflected back to the probe microphone. Group delay in children did not change with age from 5 through 12 years and was similar to adults. Group delay failed to provide an insight into the mechanism of the maturation of middle ear transmission. Few studies applied group delay or other temporal aspects of WAI for studying developmental effects in infants (Hunter et al., 2015; Keefe et al., 2015, 1993). Hunter et al. (2015) showed complex developmental patterns for group delay from birth through one month of age. Although previous studies reported group delay results in adults (Keefe et al., 1993; Robinson et al., 2016; Voss and Allen, 1994), the current study presented an initial normative database for group delay across frequencies for a large cohort of adults and children with normal hearing.

4.2 Immediate test-retest reliability

The absorbance showed high internal consistency across frequencies and age groups despite probe removal and reinsertion that may have changed the probe position within the ear canal. This is consistent with the notion that probe location inside the ear canal has minimal influence on absorbance. Others have also shown high reliability for absorbance in infants and children (Beers et al., 2010; Hunter et al., 2015, 2008). Reliability for group delay across frequencies appears to be low for all age groups, consistent with the literature (Hunter et al., 2015). Hunter and colleagues found low reliability for group delay compared to absorbance for infants. Adults showed slightly better reliability for group delay compared to children. Additionally, the reliability for group delay was much worse compared to absorbance, perhaps because the former is more dependent on the replication of the probe position in the ear canal.

4.3 Significance

The Eriksholm Workshop participants recognized that normative data collection is still in its infancy and that there is a clear need for developmental norms for WAI (Feeney et al., 2013). In addition, there was a consensus that the importance of the temporal characteristics of WAI measurements has largely been unexplored. The present study attempted to address current scientific needs in the WAI literature. The lack of a significant difference between adults and older children (10–12 years) simplifies the development of normative references for older children. However, the maturational changes in absorbance from 5 through 12 years indicate the need for developing separate normative standards. We provide the initial normative database for children. The normative characteristics of absorbance for adults—mean, confidence intervals and percentiles across frequencies—is comparable with previous studies (Liu et al., 2008; Mazlan et al., 2015), confirming good external validity. The high test-retest reliability of absorbance makes it suitable as a monitoring tool for middle ear functional status in children. Current findings do not appear to be promising for group delay

measurements in the clinic because of its poor test-retest reliability within the same test session. As the measurement approaches for WAI group delay evolves (Keefe et al., 2015; Robinson et al., 2016), it may become clinically useful in the future.

5. CONCLUSIONS

The present study described the normative features of development for WAI in children aged 5 to 12 years. Absorbance measurements are highly reliable. Absorbance matures in a frequency dependent manner with high frequencies (2828–4000 Hz) following a protracted period of development in children from 5 through 12 years of age, whereas the group delay is adult-like in the youngest tested group (5–6 years). The middle ear transmission assumes adult-like features, or becomes mature, by 10 to 12 years of age. In the future, it would be of interest to examine whether various middle ear pathologies, besides causing abnormalities, derail or delay the maturational processes for middle ear transmission in children.

Acknowledgments

This work was supported by the Hearing Health Foundation (Emerging Research Grant) and National Institutes of Health (National Institute on Deafness and other Communication Disorders R03DC014573, and National Institute of General Medical Sciences, Mountain West Clinical and Translational Research–Infrastructure Network 1U54GM104944). We greatly acknowledge Elena Fichera for data collection.

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Highlights

- Children between 5 and 9 years show maturational effects in absorbance
- Maturation of absorbance occurs in a frequency dependent manner
- Group delay is mature in children
- Maturation of middle ear transmission is complete by 10 to 12 years

Figure 1. Mean absorbance as a function of center frequencies of one-half-octave bins for all age groups (age in years). Error bars indicate 95% confidence intervals of the mean. The x-axis is slightly offset for better visualization.

Figure 2.

Mean and percentiles (5th and 95th) for absorbance as a function of frequency (211 to 6000 Hz with 23-Hz interval). The data is plotted separately for each age group of children (age in years; black color) with equivalent adult normative data (red color) as a reference. Asterisks indicate frequencies where significant adults-children differences were observed.

Figure 3.

Mean and 95% confidence intervals for absorbance across age groups for center frequencies of one-half-octave bins, where statistically significant results were observed (500, 2000 2828 and 4000 Hz). Lines connect the mean values.

Figure 4.

Mean group delay (μs) as a function of center frequencies of one-half-octave bins for all age groups. Error bars indicate 95% confidence interval of the mean. The x -axis is slightly offset for better visualization.

Table 1

Significant differences in absorbance with age ($p < 0.05$). Only frequencies of significant differences are listed.

Center Frequency (Hz)	Significant differences between children (years) and adults	Significant differences between age groups in children (years)
500	5–6 (= 0.05) 7–9 (= 0.05)	5–6 vs. 10–12 (= 0.05) 7–9 vs. 10–12 (= 0.06)
2000	5–6 (= 0.08)	5–6 vs. 10–12 (= 0.07)
2828	5–6 (= 0.11) 7–9 (= 0.09)	5–6 vs. 10–12 (= 0.08)
4000	5–6 (= 0.11) 7–9 (= 0.13)	5–6 vs. 10–12 (= 0.06) 7–9 vs. 10–12 (= 0.08)

represents the corresponding mean difference between the groups

Test-retest reliability, shown as Cronbach's α , for absorbance and group delay at center frequencies of one-half-octave-bins for each age group.

Table 2

Center Frequency (Hz)	Absorbance				Group delay			
	5-6	7-9	10-12	A	5-6	7-9	10-12	A
250	0.64	0.92	0.55	0.91	0.10	0.25	0.23	0.40
354	0.79	0.94	0.73	0.98	0.39	0.34	0.36	0.58
500	0.95	0.99	0.91	0.99	0.35	0.50	0.41	0.56
707	0.97	0.99	0.90	0.99	0.47	0.54	0.50	0.64
1000	0.99	0.99	0.98	0.97	0.52	0.50	0.48	0.70
1414	0.99	0.99	0.95	0.99	0.50	0.51	0.54	0.57
2000	0.99	0.99	0.96	0.98	0.31	0.50	0.33	0.48
2828	0.99	0.99	0.81	0.98	0.30	0.50	0.36	0.51
4000	0.99	0.99	0.75	0.99	0.40	0.41	0.45	0.60
5656	0.95	0.99	0.70	0.99	0.40	0.39	0.38	0.44