



Characterizing Age Effects on Wideband Absorbance in Normal-Hearing Children Via-Statistical and Machine Learning Analyses

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ABSTRACT

Objective: To characterize age-related changes in wideband absorbance (WBA) among normal-hearing children aged 0–6 years through combined statistical and machine learning analyses, and to establish developmental reference patterns supporting pediatric middle-ear diagnostics. **Methods:** A cross-sectional study was conducted on 579 children (1158 ears) categorized into five age groups. All participants passed age-appropriate hearing screenings. WBA was measured under both ambient pressure (AP) and tympanometric peak pressure (TPP) conditions across 16 frequencies (226–8000 Hz). Repeated-measures analysis of variance examined the effects of age, ear side, and gender, while Random Forest classifiers and principal component analysis (PCA) explored the discriminative structure and feature importance of WBA data. **Results:** Neither gender nor ear side had a significant effect on WBA patterns ($p > 0.05$). In contrast, Age significantly influenced WBA patterns ($p < 0.001$). Younger infants (< 6 months) exhibited dual-peaked “M-shaped” curves, whereas older children (3–6 years) showed single-peaked, inverted “U-shaped” profiles centered near 1600 Hz, reflecting progressive middle-ear maturation. The Random Forest model achieved a mean accuracy of 0.73 (balanced accuracy = 0.58), with the top-ranked predictors (AP₁₀₀₀, and AP₇₉₃) emphasizing low-to-mid frequency absorbance and pressure-compensation effects as key age indicators. PCA with k-means clustering further revealed partially distinct groupings aligned with chronological age, supporting the developmental encoding of WBA responses. **Conclusion:** WBA demonstrates distinct, age-dependent acoustic characteristics that correspond to physiological maturation of the middle ear. These findings provide a quantitative reference for pediatric wideband acoustic immittance and highlight the potential of machine learning in delineating developmental auditory patterns.

KEYWORDS

Wideband absorbance, Children, Middle-ear maturation, Machine learning, Normative data.

1 Introduction

Accurate evaluation of middle-ear function is fundamental in pediatric audiology, as early identification and intervention for auditory disorders can substantially influence children’s speech-language development, cognitive growth, and social-emotional well-being (Moeller, 2000). The conventional 226 Hz probe-tone tympanometry has long been the clinical standard for assessing middle-ear status (Jiang et al., 2024a). However, its narrow frequency range limits sensitivity, particularly in neonates and infants whose ear structures differ substantially from those of adults (Jiang et al., 2024b). These limitations highlight the need for diagnostic tools that can capture middle-ear function across a broader frequency spectrum during early childhood.

Wideband acoustic immittance has emerged as an advanced approach for assessing middle ear function by measuring wideband absorbance (WBA) over a broad frequency range (226–8000 Hz)

under both ambient pressure (AP) and tympanometric peak pressure (TPP) conditions (Keefe et al., 1993; Feeney and Sanford, 2004). Previous studies have shown WBA is sensitive to otitis media with effusion, ossicular chain anomalies, and other middle-ear dysfunctions across pediatric age groups (Sanford and Feeney, 2008; Prieve et al., 2013; Hunter et al., 2016). Developmental changes in tympanic membrane stiffness, ossicular mass, canal wall compliance, and middle-ear aeration collectively shape the WBA curve morphology from early infancy to childhood (Aithal et al., 2017; Myers et al., 2019; Mozaffari et al., 2021; AlMakadma et al., 2023).

Although several studies have investigated WBA across the lifespan, from newborns (Aithal et al., 2014), to infants (Myers et al., 2019), preschoolers (Beers et al., 2010), adolescents (Feeney et al., 2014), and older adults (Mazlan et al., 2015), data remain limited for East Asian children under 6 years of age. Ethnic and craniofacial variations may influence ear-canal and middle-ear acoustics

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(Beers et al., 2010; Hunter et al., 2016), emphasizing the need for population-specific normative data. Moreover, most previous studies have explored developmental trends using conventional statistical methods. Emerging evidence indicates that machine learning (ML) models can capture nonlinear and multivariate patterns within wideband acoustic immittance datasets. Recent studies have applied ML algorithms such as random forest, support vector machines, and convolutional neural networks to classify normal and pathological middle-ear conditions, achieving accuracies above 0.80 (Grais et al., 2021, 2024; Sundgaard et al., 2022; Peng et al., 2025). These advancements highlight the potential of ML to reveal subtle, age-related changes in WBA and motivate its application to characterize developmental trajectories in normal-hearing populations.

The present study aimed to characterize age-related effects on WBA in normal-hearing Chinese children aged 0–6 years by integrating statistical and machine learning analyses. By establishing developmental reference patterns and identifying key acoustic predictors of age, this study provides a comprehensive framework for understanding middle-ear maturation and improving the clinical application of wideband acoustic immittance in pediatric hearing assessment.

2 Materials and Methods

2.1 Participants

This retrospective study was approved by the Ethics Committee of the Affiliated Hospital of Xuzhou Medical University and conducted in accordance with Good Clinical Practice guidelines and the ethical principles outlined in the Declaration of Helsinki. Individual confidentiality was maintained throughout the study, and a waiver of informed consent was granted due to the retrospective nature of data collection.

Data were obtained from two primary sources: routine pediatric audiological screening records collected at the Affiliated Hospital of Xuzhou Medical University between January 2022 and August 2023, and community-based hearing screening performed at a kindergarten in Xuzhou City between May and August 2023. Participants were categorized into five age groups: Group 1 (0–3 months), Group 2 (3–6 months), Group 3 (6–12 months), Group 4 (1–3 years), and Group 5 (3–6 years). This grouping strategy was based on previous wideband acoustic immittance studies showing rapid maturational changes in external- and middle-ear function during infancy, particularly within the first year of life (Aithal et al., 2014; Hunter et al., 2016; Myers et al., 2019). Narrower intervals were therefore used during the first year of life, when developmental changes in WBA are most pronounced. In contrast, broader age intervals were used after 1 year of age because postnatal anatomical development of the external auditory canal and related conductive pathway structures continues beyond infancy, whereas the most rapid WBA-related developmental changes occur during the first year of life (Mozaffari et al., 2021). This grouping strategy also helped maintain adequate sample sizes for statistical and machine learning analyses.

Inclusion criteria were as follows: For children aged 0–3 years, auditory brainstem response (ABR) thresholds ≤ 20 dB nHL and distortion product otoacoustic emissions (DPOAE) passed, defined as $\geq 60\%$ of tested frequencies showing a distortion product ≥ -5 dB with a signal-to-noise ratio (SNR) ≥ 6 dB; For children aged 3–6 years: Normal hearing confirmed by pure-tone audiometry, with an average air-conduction threshold ≤ 20 dB HL at

500 Hz, 1000 Hz, and 2000 Hz, and without air-bone gaps; For all participants: Type A tympanogram based on 226 Hz tympanometry, no history of middle-ear or inner-ear disease, no history of adenoidectomy, tonsillectomy, or other otologic surgery. Exclusion criteria included congenital malformations of the external ear, acute tympanic membrane abnormalities on otoscopic examination; history of ear surgery or medical conditions that could affect middle-ear status.

2.2 Audiological Assessments

Pure-tone Audiometry was performed using the Aurical Aud system (Natus, Denmark) in a sound-treated booth with ambient noise levels ≤ 30 dB(A). Normal hearing was defined as an air-conduction threshold average ≤ 20 dB HL at 500, 1000, and 2000 Hz.

226 Hz Tympanometry were obtained using the OToflex middle ear analyzer (Interacoustics, Denmark), based on the Liden/Jerger classification system. Only participants with type A tympanograms were included.

Wideband Acoustic Immittance was conducted using the Titan IMP440 module (Interacoustics, Denmark). Stimuli covered a frequency range from 226 Hz to 8000 Hz. Absorbance values were recorded at 16 frequencies: 226 Hz, 324 Hz, 385 Hz, 500 Hz, 629 Hz, 793 Hz, 1000 Hz, 1259 Hz, 1587 Hz, 2000 Hz, 2519 Hz, 3174 Hz, 4000 Hz, 5039 Hz, 6349 Hz, and 8000 Hz. Measurements were obtained under both ambient pressure and peak pressure conditions, with pressure sweeping from +200 to –300 daPa.

2.3 Statistical and Machine Learning Analyses

All statistical analyses were performed using SPSS version 26.0 (IBM Corp., USA). Data normality and variance homogeneity were verified prior to inferential testing. Independent-samples t-tests examined the effects of gender and ear side on absorbance at 16 frequencies under both AP and TPP conditions, with Bonferroni correction applied ($\alpha_{\text{corrected}} = 0.0031$). Effect sizes were reported using Cohen's *d*. A repeated-measures analysis of variance was conducted with frequency as the within-subject factor and age group as the between-subject factor, evaluating both main and interaction effects. Partial eta squared (η^2) was used to quantify effect sizes. Mauchly's test revealed violations of sphericity, and Greenhouse–Geisser corrections were applied where appropriate.

For machine learning analysis, a Random Forest classifier was trained to predict age group membership using absorbance values across 16 frequencies under AP, TPP, and their difference (TPP – AP). Each ear served as one independent observation. Model performance was evaluated using five-fold stratified cross-validation, and performance metrics included overall accuracy, balanced accuracy, and macro-averaged F1 score. Feature importance analysis was performed to identify the most age-informative frequencies and pressure conditions. In addition, principal component analysis (PCA) was applied for unsupervised dimensionality reduction and visualization of developmental clustering patterns across age groups.

3 Results

A total of 579 normal-hearing children (1158 ears) were included. Participants were categorized into five age groups: Group 1 (0–3 months, $n = 44$), Group 2 (3–6 months, $n = 60$), Group 3 (6–12 months, $n = 102$), Group 4 (1–3 years, $n = 223$), and Group 5 (3–6 years, $n = 150$).

3.1 Effects of ear side and gender

Supplementary analyses indicated that neither ear side nor gender had meaningful effects on WBA. No significant differences were found between right and left ears under either TPP or AP conditions across the frequency range ($p > 0.05$). Similarly, comparisons between males and females showed no consistent differences. Although a few frequencies demonstrated statistical significance, all effect sizes were very small (Cohen's $d < 0.11$), suggesting negligible clinical impact (Supplementary Tables S1 and S2).

3.2 Age-related effects on WBA

After excluding potential confounding by ear side and gender, age was identified as the primary factor influencing WBA. Repeated-measures analysis of variance demonstrated a significant main effect of frequency under both TPP ($F(4.258, 5100.759) = 1200.045, p < 0.001, \eta^2 = 0.500$) and AP conditions ($F(4.029, 4826.246) = 928.292, p < 0.001, \eta^2 = 0.437$). Significant frequency-by-age group interactions were also observed (TPP: $F(17.031, 5100.759) = 35.492, p < 0.001, \eta^2 = 0.106$; AP: $F(16.114, 4826.246) = 24.841, p < 0.001, \eta^2 = 0.077$) (Table 1).

Pairwise comparisons confirmed that younger infants exhibited lower absorbance than older children. Group 1 (0–3 months) had significantly lower WBA than Group 4 (1–3 years) and Group 5 (3–6 years), with the largest difference observed between Groups 1 and 5 (mean difference = $-0.116, p < 0.001$). Group 2 (3–6 months) also differed significantly from Groups 4 and 5, while

comparisons among older groups yielded smaller but still significant differences (Table 2).

3.3 Developmental trends across frequencies

As shown in Figure 1, WBA curves across 16 frequencies (226–8000 Hz) demonstrated a clear developmental progression. In early infancy, curves exhibited a double-peaked, M-shaped pattern with reduced absorbance in mid-frequency regions. With increasing age, curves gradually transitioned toward a single-peaked inverted U-shaped pattern, especially evident in Groups 4 and 5. Under TPP, the peaks were more centralized and prominent, whereas under AP, curves were smoother with slightly shifted peak frequencies. Curves converged after age three, indicating functional maturation of the middle-ear system.

Figure 2 illustrates the percentile trajectories of WBA across four representative frequencies, 500, 1000, 2000, and 4000 Hz, under AP, TPP, and their difference (TPP – AP) conditions. Across both AP and TPP conditions, a progressive increase in absorbance with age was observed, particularly at low frequencies (≤ 2000 Hz). Infants younger than 6 months exhibited lower and more variable absorbance values, while children older than 3 years showed stable and higher absorbance approaching adult-like levels. The TPP–AP difference plots demonstrated that pressure equalization substantially increased absorbance in the youngest group (notably at 500 Hz). This difference gradually diminished with increasing age and was nearly negligible at 4000 Hz, reflecting

Table 1 Results of repeated-measures analysis of variance for the effects of frequency and frequency-by-age group interaction on wideband absorbance under tympanic peak pressure and ambient pressure conditions.

		Sum of Squares (Type III)	df	Mean Square	F	P	Partial Eta Squared
TPP	Frequency	365.998	4.258	85.961	1200.045	<0.001	0.5
	Frequency * Age Group	43.298	17.031	2.542	35.492	<0.001	0.106
	Frequency (Error)	365.374	5100.759	0.072			
AP	Frequency	327.08	4.029	81.19	928.292	<0.001	0.437
	Frequency * Age Group	35.011	16.114	2.173	24.841	<0.001	0.077
	Frequency (Error)	422.11	4826.246	0.087			

Note: Degrees of freedom are Greenhouse–Geisser corrected. Partial eta squared values represent effect size, with benchmarks of 0.01 (small), 0.06 (medium), and 0.14 (large). TPP = tympanometric peak pressure; AP = ambient pressure.

Table 2 Pairwise Comparison of wideband absorbance Across Different Age Groups.

Age Group Comparison	Mean Difference	Standard Error	P	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1 vs 2	-0.046	0.014	0.009	-0.085	-0.007
1 vs 3	0.031	0.013	0.128	-0.067	0.004
1 vs 4	0.074	0.012	<0.001*	0.041	0.106
1 vs 5	-0.116	0.012	<0.001*	-0.149	-0.083
2 vs 3	0.046	0.014	0.009	0.007	0.085
2 vs 4	0.078	0.011	<0.001*	0.046	0.11
2 vs 5	0.120	0.010	<0.001*	0.091	0.149
3 vs 4	-0.07	0.010	0.01	-0.099	-0.04
3 vs 5	0.042	0.008	<0.001*	0.019	0.066
4 vs 5	0.147	0.009	<0.001*	0.123	0.172

Note: Group 1 (0–3 months, $n = 44$), Group 2 (3–6 months, $n = 60$), Group 3 (6–12 months, $n = 102$), Group 4 (1–3 years, $n = 223$), and Group 5 (3–6 years, $n = 150$).

Pairwise comparisons were Bonferroni-adjusted for 10 multiple comparisons. A corrected significance threshold of $p < 0.005$ was applied. Asterisks (*) indicate statistically significant differences after correction.

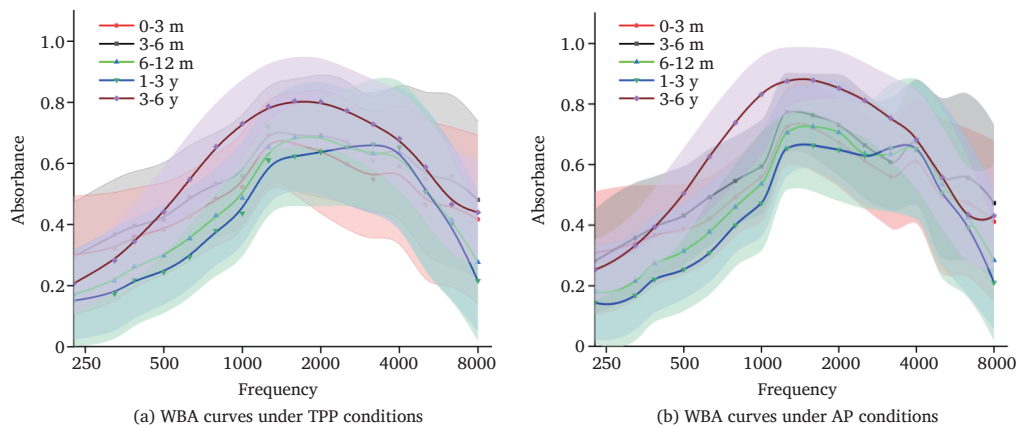


Figure 1 Age-related wideband absorbance curves under tympanic peak pressure and ambient pressure across 16 frequency points (226–8000 Hz) in normal-hearing children aged 0–6 years. Each curve represents the mean absorbance for a given age group, with shaded areas indicating the 95% confidence intervals. Across both conditions, a developmental trend is observed: WBA curves transition from a double-peaked, M-shaped configuration in infants (0–6 months) to a single-peaked, inverted U-shaped curve in older children (3–6 years). Under TPP, peaks are more centralized and prominent, especially in mid-frequency ranges. Under AP, peak frequencies are slightly elevated and curves appear smoother, likely reflecting external canal pressure effects and reduced impedance matching. The convergence of curves after age 3 suggests functional maturation of the middle-ear system. WBA = wideband absorbance; TPP = tympanometric peak pressure; AP = ambient pressure.

the progressive stabilization of tympanic membrane tension and middle-ear ventilation as the system transitions from mass- to stiffness-dominated behavior.

3.4 Machine learning analysis

To further assess whether WBA contains age-discriminative information at the individual-ear level, a Random Forest (RF) classifier was developed using absorbance values across 16 frequencies under AP, TPP, and their difference (TPP–AP) conditions. The model was trained and evaluated using five-fold stratified cross-validation. The RF model achieved a mean overall accuracy of 0.73 ± 0.02 , and a balanced accuracy of 0.58 ± 0.02 . Classification performance varied across age groups. The two youngest cohorts (0–3 and 6–12 months) were most often misclassified into adjacent groups, whereas the oldest cohort (3–6 years) exhibited the highest accuracy. Feature importance analysis identified AP_1000 Hz and AP_793 Hz as the most influential predictors, emphasizing the diagnostic relevance of low-frequency absorbance and pressure-compensation effects in age differentiation. Unsupervised principal component analysis (PCA) combined with k-means clustering ($k = 5$) revealed partially distinct group separations that aligned well with chronological age categories. These findings suggest that WBA features intrinsically encode developmental stage information, and reinforce the robustness of the observed age-dependent absorbance patterns (Figure 3).

4 Discussion

This study provides comprehensive normative data characterizing the developmental trajectory of WBA in normal-hearing Chinese children aged 0–6 years. Based on 579 participants (1158 ears), we demonstrated clear frequency- and age-dependent WBA patterns under both AP and TPP conditions. The results confirm that age is the dominant determinant of WBA variation, highlighting the rapid physiological maturation of the middle ear during early childhood (Feeney and Sanford, 2004; Hunter et al., 2016).

Across the 226–8000 Hz frequency range, absorbance curves exhibited a progressive transition from a dual-peaked, M-shaped pattern in early infancy to a single-peaked, inverted U-shaped configuration by preschool years. This morphological evolution

reflects well-documented mechanical and anatomical changes of the external and middle ear (Keefe et al., 1993; Werner et al., 2010). In neonates, the external canal is soft, cartilaginous, and highly compliant, while the tympanic membrane and ossicular chain are still developing (Rosowski and Wilber, 2015). These characteristics produce a mass-dominated system that favors higher-frequency energy transmission and contributes to the characteristic double-peaked absorbance pattern. With growth, ossification stiffens the canal wall, the tympanic membrane thickens, and ossicular ligaments tighten, leading to stiffness-dominated resonance and a single absorbance maximum near 1500–2000 Hz (Feeney and Sanford, 2004). This shift enhances impedance matching between air and cochlear fluids and reflects increasing efficiency in acoustic energy transfer across the tympanic–ossicular complex (Rosowski and Wilber, 2015). The gradual reduction of variability with age further suggests functional stabilization of middle-ear mechanics as aeration and Eustachian tube function mature (Rosowski and Wilber, 2015).

The comparison of AP and TPP conditions revealed that TPP consistently increased absorbance at low frequencies, especially near 500 Hz, and reduced variability across individuals. This effect likely arises from the normalization of negative middle-ear pressure, which improves the tension and resting position of the tympanic membrane. In younger ears, residual negative pressure, fluid viscosity or immature middle-ear ventilation may reduce sound transmission efficiency at low frequencies. Therefore, TPP adjustment may provide a more physiologically accurate reflection of true acoustic conductance. The diminishing difference between TPP and AP with increasing age supports the view that Eustachian tube opening and middle-ear aeration progressively stabilize the middle-ear system, reducing the need for pressure compensation.

Our findings demonstrated no significant differences between genders or ear sides, indicating that the observed developmental effects are physiologically consistent across populations. These results justify pooling data across gender and laterality for clinical normative references, simplifying application in pediatric diagnostics.

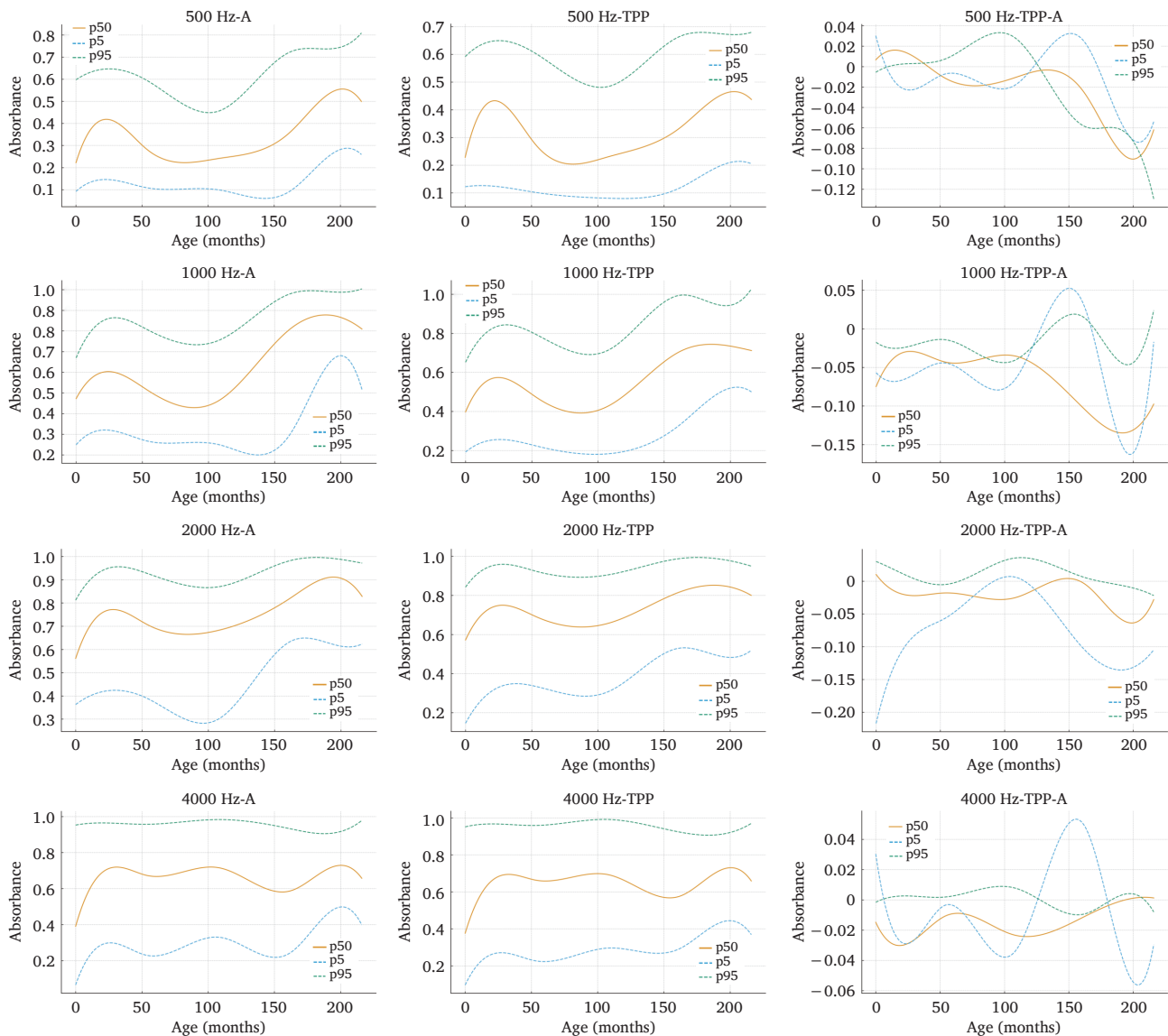


Figure 2 Representative wideband absorbance curves at four key frequencies (500, 1000, 2000, and 4000 Hz) under ambient pressure, tympanometric peak pressure, and their difference conditions. Each row corresponds to one frequency, and each column shows results under AP, TPP, and TPP – A conditions, respectively. Curves represent the 5th, 50th, and 95th percentiles across the full age range (0–6 years). TPP consistently increased absorbance at low frequencies (most notably at 500 Hz), whereas the difference between A and TPP diminished with frequency and approached zero at 4000 Hz. TPP = tympanometric peak pressure; AP = ambient pressure.

4.1 Mechanistic Integration and AI Interpretation

Previous studies have demonstrated that WBA is sensitive to middle-ear status, particularly within the low-to-mid frequency range of 500–2000 Hz (Peng et al., 2025). However, traditional group-level analyses mainly describe population averages and are limited in their ability to capture individualized developmental trajectories. In response to this limitation, the present study extends prior findings by applying machine learning (ML) approaches to determine whether individual WBA profiles encode quantifiable developmental information.

Recent ML-based studies have shown that WBA can successfully differentiate between normal and pathological middle ears, even across varying age groups (Graiss et al., 2021, 2024; Peng et al., 2025). Studies using three-dimensional WAI feature representations combined with ensemble classifiers to achieve high diagnostic accuracy for otitis media with effusion, highlighting the potential of deep and multi-feature learning to interpret subtle impedance

variations (Graiss et al., 2021, 2024). Similarly, supervised ML models could assess middle-ear function in infants based on WBA patterns, confirming that machine learning can extract physiologically meaningful spectral cues beyond conventional statistical thresholds (Peng et al., 2025). These findings collectively support the notion that data-driven models can detect intricate spectral-pressure dependencies inherent to middle-ear biomechanics.

Consistent with these reports, the Random Forest model in the present study achieved an overall accuracy of 0.73 in classifying ears into five chronological age groups, with top-ranked predictors including AP_1000 Hz and AP_793. These features correspond precisely to the frequency regions most sensitive to middle-ear maturation (Graiss et al., 2021; Peng et al., 2025). Mechanistically, the model's reliance on low-frequency absorbance aligns with established developmental transitions in tympanic membrane stiffness and middle-ear cavity aeration. During early infancy, increased compliance and reduced stiffness attenuate low-fre-

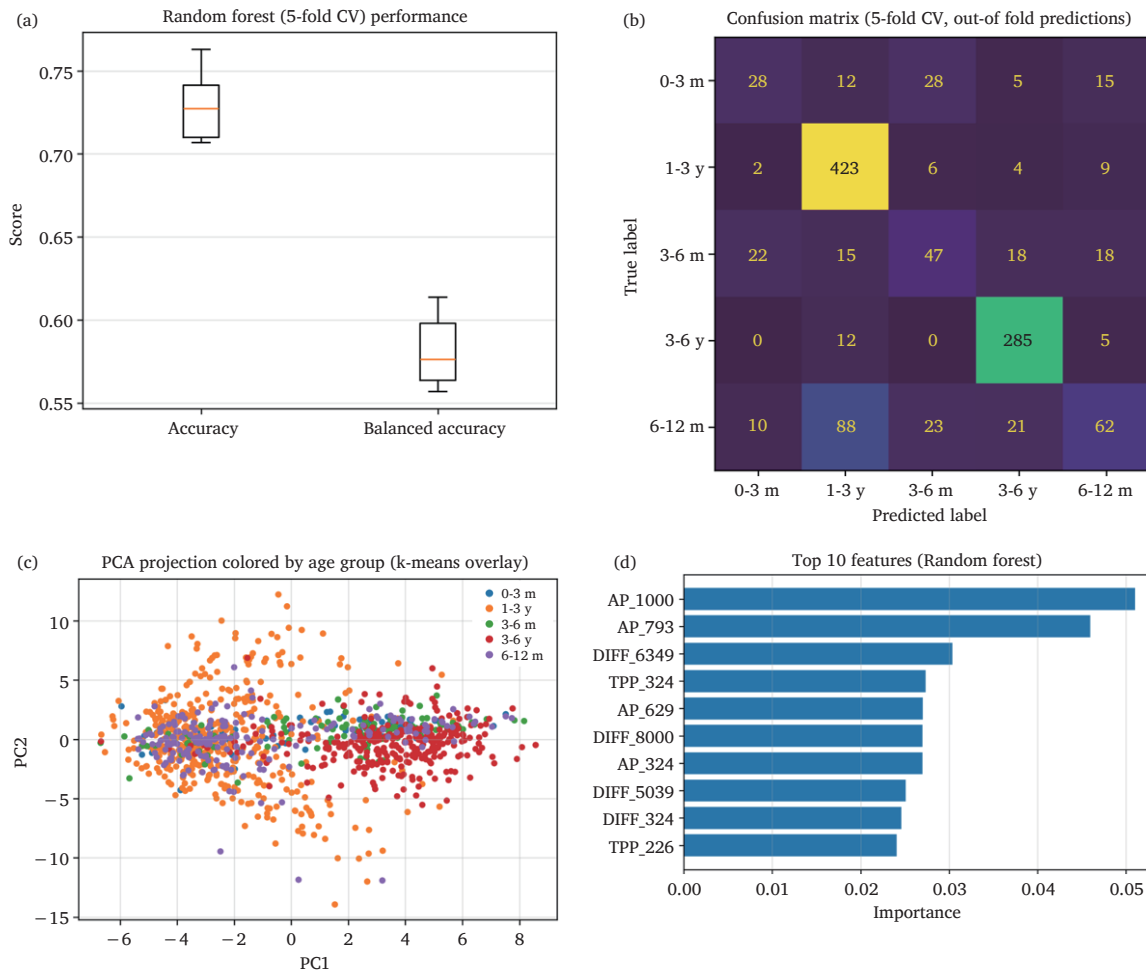


Figure 3 Machine learning analysis based on wideband absorbance data (a) Random Forest 5-fold cross-validation performance (boxplots of accuracy and balanced accuracy). (b) Confusion matrix showing classification results across the five age groups (out-of-fold predictions). (c) PCA projection of ear-level feature vectors colored by age group, with k-means ($k = 5$) clusters overlaid. (d) Top 10 features ranked by importance in the Random Forest model.

Table S1 Effect of ear side on wideband absorbance in normal group ($n = 579$)

Freq/Hz	TPP						AP					
	Right ear	Left ear	t	P	95% CI	Cohen's d	Right ear	Left ear	t	P	95% CI	Cohen's d
226	0.21 ± 0.16	0.20 ± 0.15	1.07	0.29	-0.01~0.03	0.04	0.19 ± 0.15	0.20 ± 0.16	-1.31	0.19	-0.03~0.01	-0.05
324	0.26 ± 0.17	0.25 ± 0.17	0.18	0.85	-0.02~0.02	0.01	0.24 ± 0.17	0.24 ± 0.17	-0.01	0.99	-0.02~0.02	0.00
385	0.31 ± 0.17	0.31 ± 0.17	0.14	0.89	-0.02~0.02	0.01	0.29 ± 0.16	0.29 ± 0.16	-0.02	0.98	-0.02~0.02	0.00
500	0.37 ± 0.18	0.36 ± 0.18	0.47	0.64	-0.02~0.03	0.02	0.34 ± 0.17	0.34 ± 0.18	-0.29	0.77	-0.02~0.02	-0.01
629	0.44 ± 0.20	0.44 ± 0.19	0.16	0.88	-0.02~0.02	0.01	0.40 ± 0.18	0.41 ± 0.19	-0.36	0.72	-0.03~0.02	-0.01
793	0.53 ± 0.20	0.53 ± 0.20	-0.29	0.77	-0.03~0.02	-0.01	0.49 ± 0.19	0.49 ± 0.19	-0.22	0.83	-0.02~0.02	-0.01
1000	0.60 ± 0.21	0.61 ± 0.21	-0.44	0.66	-0.03~0.02	-0.02	0.55 ± 0.20	0.54 ± 0.21	0.84	0.40	-0.01~0.03	0.03
1259	0.74 ± 0.16	0.75 ± 0.16	-0.19	0.85	-0.02~0.02	-0.01	0.69 ± 0.16	0.68 ± 0.17	1.22	0.22	-0.01~0.03	0.05
1587	0.75 ± 0.16	0.75 ± 0.16	0.50	0.62	-0.01~0.02	0.02	0.70 ± 0.17	0.69 ± 0.18	0.98	0.33	-0.01~0.03	0.04
2000	0.73 ± 0.18	0.73 ± 0.18	0.26	0.79	-0.02~0.02	0.01	0.70 ± 0.18	0.70 ± 0.20	0.40	0.69	-0.02~0.03	0.02
2519	0.68 ± 0.18	0.69 ± 0.18	-0.77	0.44	-0.03~0.01	-0.03	0.69 ± 0.19	0.68 ± 0.19	0.72	0.48	-0.01~0.03	0.03
3174	0.67 ± 0.19	0.67 ± 0.19	-0.24	0.81	-0.02~0.02	-0.01	0.67 ± 0.20	0.66 ± 0.20	0.36	0.72	-0.020.03	0.01
4000	0.66 ± 0.21	0.66 ± 0.21	-0.39	0.70	-0.03~0.02	-0.02	0.66 ± 0.21	0.65 ± 0.21	0.61	0.54	-0.02~0.03	0.03
5039	0.52 ± 0.25	0.54 ± 0.25	-1.32	0.19	-0.05~0.01	-0.05	0.54 ± 0.26	0.53 ± 0.25	1.19	0.23	-0.01~0.05	0.05
6349	0.43 ± 0.23	0.44 ± 0.23	-1.04	0.30	-0.04~0.01	-0.04	0.45 ± 0.24	0.44 ± 0.24	0.41	0.69	-0.02~0.03	0.02
8000	0.33 ± 0.23	0.33 ± 0.23	-0.20	0.84	-0.03~0.02	-0.01	0.34 ± 0.24	0.33 ± 0.24	0.05	0.96	-0.03~0.03	0.00

Note: Wideband absorbance values are presented for both tympanic peak pressure and ambient pressure conditions across 16 frequencies. No statistically significant differences were found between right and left ears at any frequency ($p > 0.05$). Effect sizes were uniformly small (Cohen's $d < 0.1$), indicating negligible clinical relevance.

Abbreviations: CI = confidence interval; SD = standard deviation; TPP = tympanic peak pressure.

Table S2 Effect of gender on wideband absorbance in normal group (n = 579)

Freq/Hz	TPP						Ambient Pressure					
	Male	Female	t	P	95%CI	Cohen's d	Male	Female	t	P	95%CI	Cohen's d
226	0.21 ± 0.15	0.21 ± 0.15	-0.88	0.38	-0.03~0.01	-0.04	0.20 ± 0.16	0.19 ± 0.15	0.54	0.59	-0.01~0.02	0.02
324	0.25 ± 0.17	0.26 ± 0.17	-0.41	0.68	-0.02~0.02	-0.02	0.24 ± 0.17	0.24 ± 0.16	0.57	0.57	-0.01~0.02	0.02
385	0.31 ± 0.17	0.31 ± 0.16	-0.51	0.61	-0.02~0.01	-0.02	0.29 ± 0.17	0.29 ± 0.16	0.10	0.92	-0.02~0.02	0.00
500	0.36 ± 0.18	0.37 ± 0.18	-0.85	0.40	-0.03~0.01	-0.04	0.34 ± 0.18	0.34 ± 0.17	0.10	0.92	-0.02~0.02	0.00
629	0.43 ± 0.20	0.45 ± 0.20	-1.22	0.22	-0.04~0.01	-0.05	0.40 ± 0.19	0.41 ± 0.18	-0.70	0.48	-0.03~0.01	-0.03
793	0.52 ± 0.20	0.54 ± 0.20	-1.48	0.14	-0.04~0.01	-0.06	0.48 ± 0.19	0.50 ± 0.18	-1.87	0.06	-0.04~0.00	-0.08
1000	0.60 ± 0.21	0.62 ± 0.21	-1.73	0.09	-0.05~0.00	-0.07	0.54 ± 0.21	0.56 ± 0.20	-2.18	0.03	-0.05~0.00	-0.09
1259	0.74 ± 0.16	0.75 ± 0.15	-2.06	0.04	-0.04~0.00	-0.09	0.68 ± 0.17	0.70 ± 0.16	-2.32	0.02	-0.04~0.00	-0.10
1587	0.74 ± 0.17	0.76 ± 0.16	-2.26	0.02	-0.04~0.00	-0.09	0.68 ± 0.19	0.71 ± 0.17	-2.57	0.01	-0.05~0.01	-0.11
2000	0.72 ± 0.18	0.74 ± 0.17	-2.00	0.05	-0.04~0.00	-0.08	0.69 ± 0.20	0.71 ± 0.18	-1.75	0.08	-0.04~0.00	-0.07
2519	0.68 ± 0.18	0.70 ± 0.17	-0.83	0.41	-0.03~0.01	-0.03	0.69 ± 0.19	0.68 ± 0.18	0.25	0.80	-0.02~0.02	0.01
3174	0.67 ± 0.19	0.67 ± 0.19	0.00	1.00	-0.02~0.02	0.00	0.67 ± 0.20	0.66 ± 0.20	0.39	0.70	-0.02~0.03	0.02
4000	0.67 ± 0.21	0.66 ± 0.21	0.81	0.42	-0.01~0.03	0.03	0.66 ± 0.21	0.65 ± 0.21	1.35	0.18	-0.01~0.04	0.06
5039	0.54 ± 0.26	0.52 ± 0.24	1.46	0.14	-0.01~0.05	0.06	0.55 ± 0.26	0.52 ± 0.25	1.50	0.13	-0.01~0.05	0.06
6349	0.44 ± 0.23	0.43 ± 0.22	0.45	0.65	-0.02~0.03	0.02	0.45 ± 0.24	0.44 ± 0.23	0.93	0.36	-0.01~0.04	0.04
8000	0.32 ± 0.23	0.34 ± 0.24	-1.02	0.31	-0.04~0.01	-0.04	0.33 ± 0.24	0.34 ± 0.24	-0.60	0.55	-0.04~0.02	-0.02

Note: Wideband absorbance values are presented for both tympanic peak pressure (TPP) and ambient pressure conditions across 16 frequencies. No statistically significant differences were found between males and females at any frequency ($p > 0.05$). Effect sizes were uniformly small (Cohen's $d < 0.1$), indicating negligible clinical relevance.

Abbreviations: CI = confidence interval; SD = standard deviation; TPP = tympanic peak pressure; AP = ambient pressure.

quency energy transfer, whereas ossification and cavity enlargement enhance absorption below 1000 Hz. Thus, the model's feature hierarchy mirrors the biomechanical tuning of the ear's resonance system as it transitions from mass- to stiffness-dominated behavior.

Furthermore, unsupervised principal component analysis revealed that ears naturally clustered according to chronological age, suggesting that WBA contains inherent low-dimensional structure related to anatomical maturation. This observation supports the hypothesis that acoustic transfer functions can serve as a noninvasive biomarker of middle-ear developmental stage, measurable even at the individual-ear level. Clinically, this integrative framework advances the conceptual shift proposed by previous researchers—from descriptive WAI metrics toward predictive, machine-learning-based modeling of auditory development (Grais et al., 2024; Peng et al., 2025). By bridging physiological insight with automated interpretation, AI-assisted WBA analysis may enable early identification of developmental deviations or otitis media susceptibility, transforming wideband absorbance into a practical tool for pediatric hearing health monitoring.

4.2 Limitations

Several limitations should be acknowledged. First, the age intervals were not evenly distributed. In particular, the 1–3-year group covered a relatively broad developmental period and accounted for a large proportion of the total sample. This internal age heterogeneity may have masked subtle WBA changes occurring between 1 and 3 years of age. Future studies with larger and more evenly distributed samples should further subdivide this age range or adopt a longitudinal design to characterize the developmental trajectory of WBA in early childhood more precisely. Second, each

ear was treated as an independent observation in the machine learning analysis, which increased the number of observations but may not fully account for within-subject correlation. Future studies should consider subject-level modeling strategies and external validation datasets to further assess the generalizability of machine-learning-based WBA classification.

5 Conclusion

This study establishes age-specific normative reference data for WBA in normal-hearing children aged 0–6 years. Developmental maturation is characterized by a shift from mass-dominated dual peaks to stiffness-dominated single peaks, most pronounced at low frequencies and under pressure-compensated conditions. Machine learning analyses confirmed that WBA profiles encode age-related physiological information, offering a potential basis for automated developmental assessment. Together, these findings underscore the value of integrating biomechanical understanding with machine-learning analytics to improve pediatric hearing diagnostics and early intervention.

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Data availability

The original data can be requested by emailing wen.jiang@xzhu.edu.cn.

Ethical approval

This study was approved by the Ethics Committee of the Affiliated Hospital of Xuzhou Medical University.

Informed consent

Not applicable.

Conflicts of interest

The authors declare no conflicts of interest.

Author contributions

J.Q. and C.F.S. analyzed the data and wrote the original draft of this article. W.J. conceptualized this project and contributed to the study design. Y.W., X.H.L. and Y.M. contributed to the data collection and analysis. F.Z. and W.L. was involved in this review. All authors reviewed, critically revised, and approved the final article.

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