

Wideband acoustic immittance (WAI) normative data in Thai normal hearing adults

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ABSTRACT

Background: The evaluation of middle ear function is important for accurately diagnosing middle ear disorders. However, conventional single-frequency tympanometry provided insufficient information to differentiate pathologies, especially in cases with normal otoscopic findings, such as otosclerosis or ossicular chain discontinuity.

Objectives: This study aimed to establish normative data for wideband acoustic immittance (WAI) measurements using stimuli across a wideband frequency range.

Materials and methods: The study focused on a Thai population with normal hearing aged 18-60 years and compared two age groups: 18-40 years and 41-60 years. A total of 245 participants were included in this study. WAI measurements were performed for wideband absorbance (WBA), resonance frequency, tympanic peak pressure, and ear canal volume.

Results: The WBA_0 and WBA_{TPP} gradually increased from the lowest value at 226 Hz to the highest at 3174.8 Hz. The analysis revealed no statistically significant differences in WBA_0 and WBA_{TPP} between the two age groups. However, statistically significant differences were observed in WBA_0 and WBA_{TPP} between sexes.

Conclusion: This study provides normative data for WBA_0 and WBA_{TPP} in adults with normal middle ear function. The overall absorbance patterns were generally comparable to those reported in previous studies.

Introduction

Middle ear diseases can occur in both children and adults, often resulting from infectious inflammation or functional abnormalities. Clinical presentation varies according to the underlying pathophysiology and may include otorrhea, otalgia, hearing loss, and tinnitus. The effects of middle ear diseases in children include delayed speech and language development,¹ whereas in adults these disorders are associated with hearing-related communication difficulties, reduced work performance, social participation, adverse psychological effects such as anxiety and decreased self-confidence,² impaired communicative functioning secondary to hearing loss, and an overall reduction in quality of life.³ A non-invasive, cost-effective diagnostic

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tool that can differentiate among various middle ear diseases would be highly valuable in clinical practice. Acoustic immittance is important for the accurate diagnosis of middle ear diseases and facilitates timely treatment. This is essential for minimizing the duration of hearing loss and its impact on the patient's quality of life and communication abilities.

The single-frequency method at 226 Hz is the most used for evaluating middle ear function. This approach provides information on the movement of the tympanic membrane and ossicles in the middle ear, middle ear pressure, and ear canal volume. This method has limitations in diagnosing certain conditions and may provide insufficient information to differentiate middle ear pathologies, especially when the tympanic membrane is normal. Consequently, this can lead to inaccuracies and variability in the interpretation of results. This limitation has prompted the development of *wideband acoustic immittance (WAI)*, which uses a broadband frequency range (e.g. click) to provide more detailed data and greater specificity in diagnosing middle ear dysfunction across different conditions. WAI evaluates various middle ear functions, including absorbance, reflectance, conductance, and admittance, offering a more comprehensive assessment than single-frequency testing.⁴ Absorbance and reflectance are particularly used to assess sound absorption and reflection in the middle ear. Different pathologies affect reflectance and absorbance values in different ways, depending on the specific condition. Therefore, resulting in a range of WAI values. Voss *et al.*⁵ found that power reflectance graphs differed among conditions of otosclerosis, ossicular chain discontinuity, and superior canal dehiscence. Karuppanan and Barman⁶ reported that absorbance patterns in the ossicular chain discontinuity group were distinctly different from those in the normal ear group and the otosclerotic ear group. Moreover, Wang *et al.*⁷ and Sliwa *et al.*⁸ observed that absorbance values in individuals with otosclerosis were lower than in normal ears, with sensitivity and specificity exceeding 85%.

The data indicates that WAI provides more comprehensive information than current methods and may be beneficial for further diagnosing middle ear diseases, in addition to the single-frequency acoustic immittance currently in use. However, WAI results can vary based on several factors, including age, ethnicity, and middle ear pathology.^{9,10} Previous reports have suggested that differences in wideband absorbance characteristics may occur around 40 years of age.^{10,11} Normative data studies from different countries have shown variations in test results and graph characteristics.

This study aimed to establish normative data for WAI measurements in the Thai population. This data will facilitate comparisons between individuals with normal hearing and patients with middle ear disorders involving pathologies behind the tympanic membrane, thereby supporting future diagnostic research.

Materials and methods

Participants

All participants with normal hearing, aged 18 to 60 years, were recruited from the Otorhinolaryngology Outpatient Departments at Srinagarind Hospital, Khon Kaen University; Songklanagarind Hospital, Prince of Songkla University; and Maharaj Nakorn Chiang Mai Hospital, Chiang Mai University, Thailand, between January and April 2024. Participants were categorized into two age groups: 18-40 years (N=139) and 41-60 years (N=106). All participants had normal external ear canal and tympanic membrane findings, with no history of middle ear disorders or middle ear surgery and met all inclusion criteria including: 1) AC ≤ 25 dBHL (250-8000 Hz) and air-bone gap ≤ 10 dBHL, 2) Type A tympanogram (226 Hz) with present ipsilateral acoustic reflex, 3) No diagnosis of middle ear disease or no history of middle ear surgery, and 4) Normal otoscopic examination and tympanic membrane. The exclusion criteria included 1) otalgia, 2) Type A_s, A_d, B, or C tympanogram (226 Hz), and 3) non-cooperation with audiometric measurement or inability to complete the evaluation.

Instrumentation

Pure-tone audiometry data were collected in a soundproof booth using an AC40 audiometer (Interacoustics, Denmark) with a DD45 audiometer headset, 3M Peltor H7A earmuffs, or IP30 insert earphones for air-conduction testing, and a B-81 bone transducer headset for bone-conduction testing. WAI measurements were obtained using the Titan Suite IMP440/WBT440 system (Interacoustics, Denmark). Prior to data collection, the system underwent probe calibration according to the manufacturer's instructions to ensure accurate stimulus delivery and recording. The measurements were performed using the instrument's default calibration settings.

Procedure

Air-conduction pure-tone audiometry at frequencies of 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz, and bone-conduction audiometry at 500, 1000, 2000, and 4000 Hz were performed in a soundproof booth. WAI measurement was conducted using click stimuli covering frequencies from 226 to 8000 Hz with a 1/24-octave bandwidth at a stimulus level of 100 dBpeSPL (decibels peak-equivalent sound pressure level). The click stimulus was presented at a rate of 21.5 Hz. Measurements were obtained using a continuous pressure sweep from +200 to -200 daPa. Participants were instructed to remain seated and avoid talking or swallowing during testing. The probe tip size was selected to achieve an adequate seal within the ear canal. To ensure reliable measurements, probe calibration and routine system checks were performed at the beginning of each testing session throughout the study period. All WAI results (e.g., WBA₀, WBA_{TPP}, tympanic peak pressure, ear canal volume, and resonance

frequency) were recorded by Titan Suite, using a research license and exported as raw .m-files.

Statistical analysis

Descriptive statistics, including the median, quartiles, and percentiles, were calculated using SPSS version 28 for Windows for data analysis, with a significance level of 0.05. The Shapiro-Wilk test was applied to assess the normality of absorbance, resonance frequency, tympanic peak pressure (TPP), and ear canal volume (ECV). The results showed that these variables were not normally distributed. Consequently, the Mann-Whitney U test was used to compare age groups and sexes, given the non-normal distribution of the data.

Results

A total of 369 individuals were interested in participating; however, only 245 participants (490 ears) met the inclusion criteria and were enrolled in the study.

Among these, 148 were female (296 ears), and 97 were male (194 ears). The demographic data, categorized by sex and age group (18-40 years and 41-60 years), with a median participant age of 36 years, are presented in Table 1. The results for resonance frequency, middle ear pressure (tympanic peak pressure), and ear canal volume of participants in both age and sex groups, analyzed using descriptive statistics and presented as the median, Q1, and Q3 are shown in Table 2. The study presents the absorbance values at ambient pressure (WBA_0) and at the point of highest admittance (WBA_{TPP}) for all participants. Using descriptive statistics, including the median and percentiles (10th, 25th, 75th, and 90th), are provided for 16 frequencies (1/3 octave) as shown in Table 3.

The WBA_0 and WBA_{TPP} values gradually increased from their lowest, 226 Hz, to their highest, 3174.8 Hz. After reaching this peak, the absorbance values began to decrease at 4000 Hz and continued to decline up to 8000 Hz, as shown in Figure 1.

Table 1. Demographic data of the participants.

Age groups	Ears	Age (years) Median (min, max)	Female, N (%)	Male, N (%)
Total	490	36 (18, 59)	296 (60.4)	194 (39.6)
18-40 years	278	28 (18, 40)	164 (59.0)	114 (41.0)
41-60 years	212	46 (41, 59)	132 (62.3)	80 (37.7)

Table 2. Median, Q1, and Q3 values for resonance frequency, middle ear pressure (tympanic peak pressure), and ear canal volume.

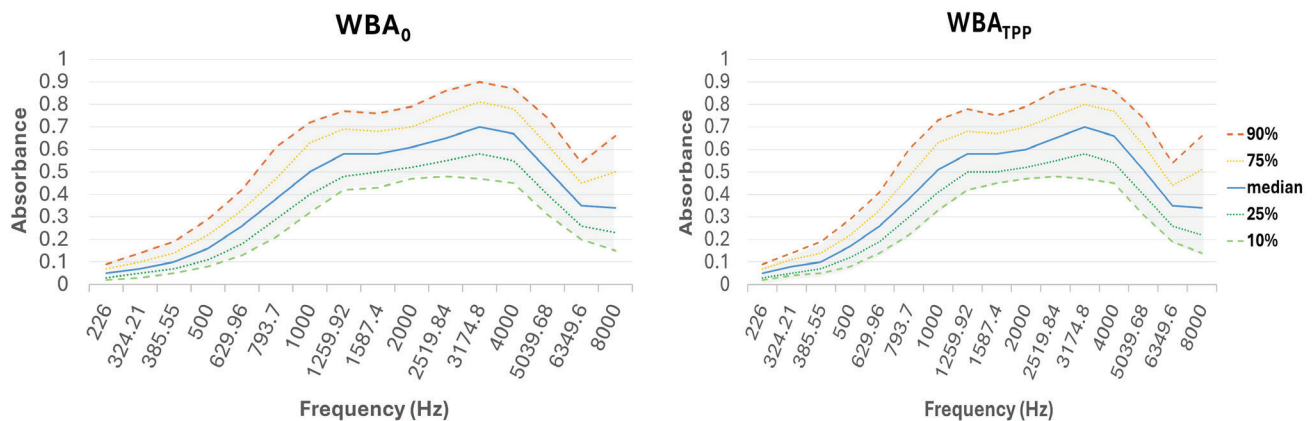
Group	Resonance frequency (Hz) Median (Q1, Q3)	p value	Tympanic peak pressure (daPa) Median (Q1, Q3)	p value	Ear canal volume (cm ³) Median (Q1, Q3)	p value
Total (490 ears)	1022.5 (882, 1148)		-7 (-12, -2)		0.95 (0.80, 1.11)	
Age group						
18-40 yrs (278 ears)	1036 (882, 1177)		-7 (-12, -2)		0.99 (0.81, 1.14)	
41-60 yrs (212 ears)	997 (873, 1108.5)	0.05	-7 (-12, -2)	0.89	0.92 (0.77, 1.06)	0.01*
Sex						
Female (296 ears)	1032 (890.50, 1174.75)		-6.00 (-11.75, -1.25)		0.89 (0.75, 1.05)	
Male (194 ears)	987 (867, 1113.25)	0.13	-7.00 (-12, -3)	0.30	1.04 (0.90, 1.17)	<0.001*

Note: Q1: 1st quartile, Q3: 3rd quartile.

Table 3. Median and percentiles (10th, 25th, 75th, and 90th) for absorbance at ambient pressure (WBA₀) and absorbance at peak admittance (WBA_{TPP}).

Frequency (Hz)	WBA ₀					WBA _{TPP}				
	Median	10%	25%	75%	90%	Median	10%	25%	75%	90%
226	0.05	0.02	0.03	0.07	0.09	0.05	0.02	0.03	0.07	0.09
324.21	0.07	0.03	0.05	0.10	0.14	0.08	0.04	0.05	0.11	0.14
385.55	0.10	0.05	0.07	0.14	0.19	0.10	0.05	0.07	0.14	0.19
500	0.16	0.08	0.11	0.22	0.29	0.17	0.08	0.12	0.22	0.29
629.96	0.26	0.13	0.18	0.33	0.42	0.26	0.14	0.19	0.33	0.41
793.7	0.38	0.21	0.29	0.47	0.61	0.38	0.22	0.30	0.48	0.60
1000	0.50	0.32	0.40	0.63	0.72	0.51	0.33	0.41	0.63	0.73
1259.92	0.58	0.42	0.48	0.69	0.77	0.58	0.42	0.50	0.68	0.78
1587.4	0.58	0.43	0.50	0.68	0.76	0.58	0.45	0.50	0.67	0.75
2000	0.61	0.47	0.52	0.70	0.79	0.60	0.47	0.52	0.70	0.79
2519.84	0.65	0.48	0.55	0.76	0.86	0.65	0.48	0.55	0.75	0.86
3174.8	0.70	0.47	0.58	0.81	0.90	0.70	0.47	0.58	0.80	0.89
4000	0.67	0.45	0.55	0.78	0.87	0.66	0.45	0.54	0.77	0.86
5039.68	0.51	0.31	0.40	0.62	0.74	0.51	0.31	0.40	0.62	0.74
6349.6	0.35	0.20	0.26	0.45	0.54	0.35	0.19	0.26	0.44	0.54
8000	0.34	0.15	0.23	0.50	0.66	0.34	0.14	0.22	0.51	0.66

Note: Bold indicates peak median WBA.

**Figure 1.** WBA₀ and WBA_{TPP} values for all participants.

In this study, the results showed no statistically significant difference in resonance frequency and tympanic peak pressure. However, the ear canal volume in the 18-40 years group was significantly larger than in the 41-60 years group ($p < 0.05$). No statistically significant differences were observed in resonance frequency and tympanic peak pressure between males and females. However, males had a significantly larger ear canal volume compared to females ($p < 0.05$). The comparison of the median values of WBA₀ and WBA_{TPP}

between the 18-40 years and 41-60 years age groups revealed no statistically significant differences at any frequency (Figure 2). Moreover, the comparison of the median values of WBA₀ and WBA_{TPP} between females and males revealed statistically significant differences ($p < 0.05$) at the frequencies 226 Hz, 324.21 Hz, 385.55 Hz, 500 Hz, 629.96 Hz, 793.70 Hz, 1000 Hz, 4000 Hz, 5039.68 Hz, and 8000 Hz for both WBA₀ and WBA_{TPP}, as shown in Figure 3.

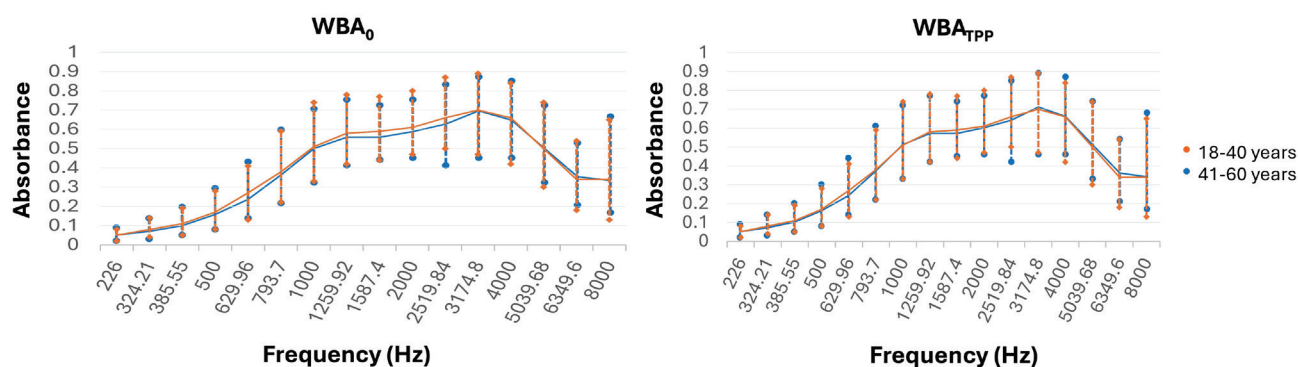


Figure 2. Median WBA_0 and WBA_{TPP} values across frequencies for the 18-40- and 41-60-year age groups.

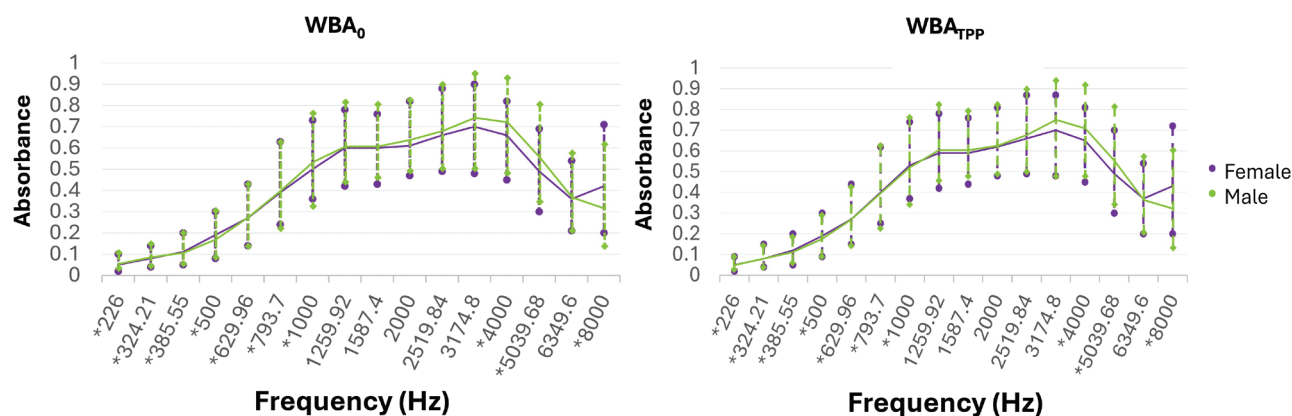


Figure 3. Median WBA_0 and WBA_{TPP} values across frequencies for the female and male participants.

Discussion

Wideband acoustic immittance (WAI) testing provides valuable diagnostic information, and establishing normative values is important for its clinical application. Previous studies have suggested that WAI measurements may vary across populations. Therefore, this study was conducted in three hospitals located in different regions of Thailand to include participants from geographically diverse areas. We focused on healthy adults and excluded individuals from extreme ages. The median tympanic peak pressure was -7 daPa, which is within the normal range of ± 100 daPa observed in healthy individuals.¹² The average ear canal volume was 0.95 cm^3 (within the typical adult range of 0.6 to 2.0 cm^3).¹³ The median resonance frequency was 1022.5 Hz, which is close to the range reported in another study for normal individuals (1100-1800 Hz).⁴

Resonance frequency reflects the combined mass-stiffness characteristics of the middle ear system. Variations in anatomical structures of the external and middle ear, including ear canal volume (ECV) and middle ear cavity properties, may influence these acoustic characteristics. In the present study, no significant differences in resonance frequency were observed between age groups or sexes. Similar findings have been reported by Kavruk and Öztürk¹⁴ and Simic¹⁵,

who also found no significant age-related differences in resonance frequency among adults. These results may indicate that the mass-stiffness balance of the middle ear system remains relatively stable throughout adulthood. Nevertheless, individual variability in resonance frequency may still be influenced by anatomical factors such as ear canal dimensions. For example, Özgür *et al.*¹⁶ reported significant differences in resonance frequency in early infancy compared with older age groups, suggesting that developmental changes in ear canal and middle ear structures may affect resonance frequency measurements. Regarding sex differences, Shahnaz and Davies¹¹ reported no significant difference between males and females, whereas Özgür *et al.*,¹⁶ and Simic¹⁵ reported that resonance frequency was significantly higher in females than in males. These findings suggest that anatomical differences between sexes may contribute to variability in acoustic immittance measurements. However, the lack of significant differences in resonance frequency observed in the present study may indicate that these anatomical variations did not substantially alter the mass-stiffness characteristics of the middle ear system within the studied population.

Regarding tympanic peak pressure, no significant differences were observed among the age groups, consistent with the findings of Mazlan *et al.*¹⁰ Kavruk and

Öztürk¹⁴ reported no significant differences between the groups of 20-39 years and 41-60 years, or between 41-60 and 65-82 age groups; however, the tympanic peak pressure was significantly higher in the group of 65-82 years compared to the 20-39 years group, which is beyond our studied age group. Downing *et al.*¹⁷ also indicated that age affects tympanic peak pressure, with higher tympanic peak pressure associated with increasing age. Additionally, our study found no statistically significant difference in tympanic peak pressure between females and males, consistent with the findings of Wan and Wong¹⁸ Shahnaz and Davies¹¹ and Simic.¹⁵

We found that ear canal volume was significantly greater in the 18-40-year group than in the 41-60-year group. Previous studies in adults have generally reported no significant effect of age on ear canal size. For example, Sinha *et al.*¹⁹ Mazlan *et al.*¹⁰ and Kennet²⁰ found that ear canal volume remained relatively stable across adult age groups. Therefore, the difference observed in the present study may reflect individual anatomical variability rather than a consistent age-related trend. In addition, the present findings indicate that ear canal volume was significantly larger in males than in females. This observation is consistent with previous studies^{11,14,15,21,22} and may be related to larger overall craniofacial and body dimensions in males.

Humes *et al.*²³ examined the effects of age, sex, and race/ethnicity on WAI values, and numerous small-sample studies of clinical populations have explored the sensitivity of WBA measures to various middle ear disorders.^{8,24,25} Variations in absorbance across frequencies reflect the mass and stiffness characteristics of the middle ear system. Increased mass or stiffness increases impedance and reduces absorbance. Consequently, absorbance is typically lower at low frequencies, reaches a maximum near the resonance frequency, where impedance is minimal, and decreases again at higher frequencies (>3000 Hz) due to dominant mass effects.²⁶ Thus, abnormal changes in stiffness affect low-frequency absorbance, while changes in mass impact high-frequency absorbance. This study observed that WBA₀ and WBA_{TPP} values increase from a minimum at 226 Hz to a maximum at 3174.8 Hz, then decrease from 4000 Hz to 8000 Hz, a pattern similar to that reported in other studies.^{21,22,27-31} However, these results differ from those in other countries, possibly due to ethnic variations affecting absorbance values.^{8,10,32,33} The results from studies conducted in populations with ethnic backgrounds most similar to that of the present study, particularly those by Özgür *et al.*¹⁶ in the Turkish population and Habibi *et al.*³⁴ in young Iranian adults, showed WBA₀ and WBA_{TPP} values that were more comparable to our findings than those reported in studies from more geographically distant populations.

No statistically significant differences in absorbance were found between the 18-40 and 41-60 age groups

in this study. Şahin and Aksoy³¹, who reported no differences in absorbance among the age groups of 20-29, 30-39, and 40-49 years. However, Downing *et al.*¹⁷ found significant differences in WBA₀ at 250, 1250, and 3150-5000 Hz, and in WBA_{TPP} at 250, 1000, and 3150-5000 Hz among the age groups of 4-6, 7-9, and 10-13 years. Kavruk and Öztürk¹⁴ found no significant differences in WBA₀ across the age groups 20-39, 41-60, and 65-82 years. They noted that WBA_{TPP} increased at low frequencies up to 1000 Hz with age but decreased to 1587-3175 Hz. Mishra *et al.*³⁵ similarly reported lower WBA₀ at 500 Hz in younger than in older children, and a decrease in absorbance at 2000, 2828, and 4000 Hz with age, which they attributed to increased middle ear mass and impedance.¹⁷ In this study, significant differences were observed between males and females in both WBA₀ and WBA_{TPP} at frequencies 226, 324.21, 385.55, 500, 629.96, 793.70, 1000, 4000, 5039.68, and 8000 Hz ($p < 0.05$). Males had higher values at frequencies of 226, 324.21, 385.55, 500, 629.96, 793.70, 1000, and 8000 Hz, whereas females had higher values at 4000 and 5039.68 Hz. These findings are consistent with those reported by Özgür *et al.*,¹⁶ and Mazlan *et al.*,¹⁰ who observed higher low-frequency absorbance in males and lower high-frequency absorbance in females. Similar findings were reported by Kenn³⁶, Polat *et al.*,²¹ and Simic.¹⁵ In addition, Kavruk and Öztürk¹⁴ demonstrated that males exhibited higher mean absorbance at frequencies below 1000 Hz, whereas females showed higher mean absorbance at higher frequencies. In contrast, Beers *et al.* and Downing *et al.* found no significant sex differences in WBA₀, whereas Freeney *et al.* reported significant differences above 1300 Hz but not below 1000 Hz. Variability across studies may reflect differences in participant characteristics and anatomical factors.

In the present study, ear canal volume differed between age groups; however, wideband absorbance did not differ significantly between groups. This finding suggests that the variation in ear canal volume observed in this sample did not substantially influence wideband absorbance measurements. Differences in study populations, as well as variations in study design and measurement protocols, may also contribute to discrepancies reported across studies.

Limitations

Although this study was conducted in three hospitals located in different parts of Thailand to represent the nationwide population, more detailed information on ethnicity, such as familial and ancestral background, could better clarify the distinct ethnic variations that may influence absorbance values. Furthermore, future normative studies focusing on more geographically homogeneous populations could strengthen normative data by allowing more precise evaluation of ethnic effects.

Conclusion

This study provides reference values for WBA_0 and WBA_{TPP} in Thai adults aged 18-60 years with normal middle ear function. Significant differences in absorbance between males and females suggest that sex-specific reference values may be considered. The overall absorbance pattern was generally comparable to previous reports, although some variation in median values was noted across populations. These findings may contribute to the development of population-specific reference data for clinical and research applications.

Ethical approval

The research was conducted in accordance with the Declaration of Helsinki, and approved by the Khon Kaen University Ethics Committee Faculty of Medicine, on December 26, 2023 (HE661552), Research Ethics Committee Faculty of Medicine, Chiang Mai University, on December 26, 2023 (ENT-2567-0023) and Human Research Ethics Unit (HREU), Prince of Songkla University, on February 9, 2024 (REC.67-0086-13-1).

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Conflict of interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Thanawan Wongkor: conceptualization, methodology, investigation, data curation, data collection, formal analysis, writing: original draft; **Nichtima Chayaopas:** conceptualization, methodology, supervision, validation, writing: review and edit; **Supawan Laohasiriwong:** conceptualization, methodology, supervision, writing: review and edit; **Pittayapon Pitathawatchai:** conceptualization, writing-review and editing; **Sanathorn Chowsilpa:** conceptualization, writing: review and edit.

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