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WIDEBAND ABSORBANCE PATTERNS IN ADULTS WITH CENTRAL AND MARGINAL TYMPANIC MEMBRANE PERFORATION

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
G Funds collection

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Abstract

Introduction: This study aimed to investigate the impact of central and marginal tympanic membrane perforations (TMP) on wideband absorbance (WBA) and compare it with normal ears.

Material and methods: Three groups of individuals, aged 18 to 50 years: Group I with central TMP ($n = 65$), Group II with marginal TMP ($n = 13$), and Group III with normal middle ears ($n = 20$) were considered. WBA measurements were performed at peak and ambient pressure conditions across frequencies.

Results: Significant differences in WBA were observed between the groups with central and marginal TMP and the normal ear group across all frequencies. Central TMP exhibited decreased absorbance at low frequencies and increased absorbance at high frequencies, peaking at 5000 Hz. Marginal TMP showed peaks at 600, 4000, and 6000 Hz with decreased absorbance at 2000 Hz. Central TMP exhibited lower absorbance than marginal TMP at lower frequencies, while marginal TMP showed decreased absorbance at mid and high frequencies.

Conclusions: These findings highlight the role of WBA in differentiating normal ears from those with TMP. Understanding TM vibration patterns and frequency-dependent variations in absorbance enhances diagnostic accuracy and clinical management.

Keywords: wideband absorbance tympanometry • tympanic membrane • central perforation • marginal perforation • peak/ambient pressure

WZORCE SZEROKOPASMOWEJ ABSORBANCJI U DOROSŁYCH Z CENTRALNĄ I BRZEŻNĄ PERFORACJĄ BŁONY BĘBENKOWEJ

Streszczenie

Wprowadzenie: Niniejsze badanie miało na celu ocenę wpływu centralnych i brzeżnych perforacji błony bębenkowej (ang. *tympanic membrane perforations*, TMP) na absorbancję szerokopasmową (WBA) i porównanie jej z wynikami uszu z nieuszkodzoną błoną bębenkową.

Materiał i metody: W badaniu uczestniczyły trzy grupy osób w wieku od 18 do 50 lat: grupa I z centralną TMP ($n = 65$), grupa II z brzeżną TMP ($n = 13$) i grupa III z nieuszkodzoną błoną bębenkową ($n = 20$). Pomiary WBA przeprowadzono w warunkach ciśnienia szczytowego i ciśnienia otoczenia w różnych częstotliwościach.

Wyniki: Zaobserwowano znaczące różnice w WBA między grupami z centralną i brzeżną TMP a grupą z nieuszkodzoną błoną bębenkową we wszystkich częstotliwościach. Centralna TMP powodowała zmniejszoną absorbancję przy niskich częstotliwościach i zwiększoną absorbancję przy wysokich częstotliwościach, z wynikiem szczytowym na 5000 Hz. Brzeżna TMP wykazywała wartości szczytowe na 600, 4000 i 6000 Hz, a zmniejszoną absorbancję na 2000 Hz. Centralna TMP powodowała niższą absorbancję w porównaniu z brzeżną TMP na niższych częstotliwościach, podczas gdy brzeżna TMP powodowała obniżoną absorbancję na średnich i wysokich częstotliwościach.

Wnioski: Odkrycia te podkreślają rolę WBA w różnicowaniu uszu z nieuszkodzoną błoną bębenkową od tych z TMP. Zrozumienie wzorców wibracji TM i zależnych od częstotliwości zmian absorbancji zwiększa dokładność diagnostyczną i wpływa na postępowanie kliniczne.

Słowa kluczowe: tympanometria szerokopasmowa • błona bębenkowa • perforacja centralna • perforacja brzeżna • ciśnienie szczytowe/otoczenia

Key for abbreviations

WBT	wideband tympanometry
WBA	wideband absorbance
TM	tympanic membrane
TMP	tympanic membrane perforation

Introduction

The primary function of tympanic membrane (TM) is to transmit sound waves effectively from the external auditory canal through the ossicular chain to the oval window and inner ear. This crucial process relies on the vibratory nature of the TM, i.e., it converts the ear canal's sound pressure to the ossicles' vibrations [1]. The TM can be divided into four quadrants: anterosuperior, anteroinferior, posteroinferior, and posterosuperior [2]. Studies have shown that the TM exhibits frequency-specific transmission, indicating its importance in sound transduction [3,4]. However, depending on their location and extent, tympanic membrane perforation (TMP) can have varying effects on sound transmission.

TMP can be classified according to the perforation site, whether on the pars tensa or pars flaccida. Central TMP may involve different quadrants of the TM, with anterior quadrant TMP extending from the anterior to the malleus handle, and posterior quadrant TMP extending from the posterior to the handle of the malleus. Marginal TMP involves a lack of TM borders in specific segments [5] and the location of the perforation can alter frequency-specific sound transmission to the ossicles.

Although single-frequency tympanometry with a 226-Hz probe tone is a commonly used diagnostic tool for evaluating the middle ear system, some studies have reported low accuracy in identifying middle ear pathologies [6,7]. This is because middle ear disorders produce a significant change in middle ear structures, including the ossicular mass, stiffness of the TM, and supporting structures, which leads to frequency-specific attenuation or filtering [8]. To overcome these limitations, multi-frequency tympanometry is used, which is superior to standard 226 Hz tympanometry. However, it has limitations, such as standing waves above 1500 Hz, which result in significant differences in sound pressure levels within the ear canal and, thus, can interfere with accurate readings at high frequencies [9,10]. To address these challenges, wideband tympanometry (WBT) emerged as an alternative tool to assess the middle ear system.

WBT measures the amount of sound energy absorbed or reflected by the ear. A controlled range of sounds is introduced into the ear canal, and then an analysis is performed on how much of that energy is absorbed or reflected by the eardrum at each frequency. This information provides insights into the functioning and characteristics of the middle ear [11,12].

The impact of TMP on wideband absorbance (WBA) measures on middle ear transmission has been discussed in several studies [13–18]. Karuppannan and Barman (2021) [15] and Karuppannan et al. (2024) [19] found lower absorbance values in low and mid frequencies, with higher absorbance observed beyond 4000 Hz under peak pressure conditions for individuals with TMP. Similarly, Kim et al. (2019) [17] conducted WBA on individuals with TMP and noted lower absorbance at low frequencies and higher absorbance at high frequencies. However, inconsistencies in the literature have been reported, with some studies [20,21] indicating higher absorbance at low frequencies in individuals with TMP. Overall, no consensus exists regarding frequencies with highly variable energy absorbance patterns reported in individuals with TMP.

This variability in absorbance patterns may be attributed to the inclusion of different types and locations of TMP. Even though some studies have shown that the size of the TMP has more of an impact on transmission than its location [22], the fact is that the location of a TMP significantly alters frequency-specific sound transmission [23,24]. It is therefore essential to study the effect of the location of TMP on WBA. However, no studies have compared WBA across different quadrants of the TMP, which is a research gap. Thus, the current study investigated the effect of the two types of TMP on WBA measures. The objectives were to compare, against normal ears with intact TM and under different pressure conditions, WBA across frequencies for the two TMP types.

Material and methods

Participants

Three groups of participants, aged between 18 and 60 years (mean age 35.2 years; *SD* = 9.7 years), were recruited for the study. Group I comprised individuals with central TMP (mean age, 36.3 years; *SD* = 6.7 years) (*n* = 65 ears); Group II included participants with marginal TMP (mean age, 32.6 years; *SD* = 4.5 years) (*n* = 13 ears), and Group III was the normal ear group, consisting of individuals with intact TM and normal hearing sensitivity (mean age 31.2 years; *SD* = 2.5 years) (*n* = 20 ears).

The study obtained ethical approval from the Ethical Committee for Bio-Behavioural Research Involving Human Subjects at the All India Institute of Speech and Hearing (approval no. WOF-0404) and adhered to the ethical principles outlined in the Helsinki Declaration (2013) for medical research involving human subjects. The study's objectives and procedures were explained in detail to each participant, and written informed consent was obtained for their voluntary participation before enrolment in the study.

Criteria for inclusion

The normal ear group (Group III) had air conduction hearing thresholds of ≤ 15 dB HL in the octave frequencies between 250 and 8000 Hz, an air-bone gap of ≤ 10 dB HL, speech identification scores of > 90%, and uncomfortable loudness level (UCL) of > 90 dB HL. All participants exhibited normal middle ear, as confirmed by single frequency immittance findings showing an "A/As" type tympanogram with both ipsi- and contralateral reflexes present between 90 and 100 dB HL, along with the presence

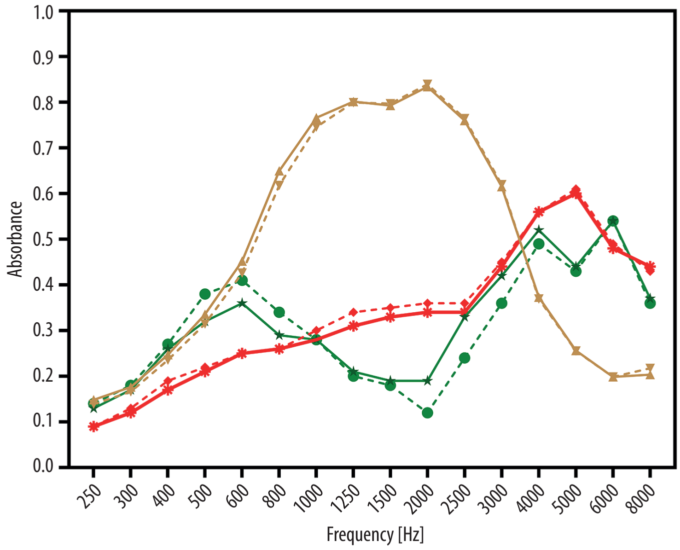

Figure 1. Mean WBA values across frequency of the normal ear group (brown), central TMP group (red), and marginal TMP group (green) as obtained at peak pressure (continuous lines) and ambient pressure (dotted lines)

of transient evoked otoacoustic emissions (TEOAEs) characterized by a signal-to-noise ratio (SNR) > 6 dB and reproducibility of > 85%.

Ears with central and marginal TMP (Group I and II) exhibited isolated dry TMP, i.e., without any active discharge and with no other pathologies associated with the TMP. In central TMP, the perforation was localized around the umbo or malleolar handle (*pars tensa* region), with the TM remaining intact around the bony canal. Marginal TMP was confined to the TM margins. These findings were confirmed by an experienced otologist. Ears with TMP (central and marginal) had conductive hearing loss (air-bone gap > 10 dB) and a pure tone average not exceeding 60 dB HL. Tympanometry revealed a "B" type tympanogram [11] with an absent measurable peak using a 226 Hz probe tone and absent acoustic reflexes between 500 and 4000 Hz at octave frequencies.

Procedure

Participants were seated comfortably during the experiment without any movement. Each participant was informed of the testing methods, which involved inserting a probe tip into the ear canal to create an airtight seal, generating pressure, and presenting click stimuli. Titan Suite IMP440 v. 3.0 was used for WBA measurements. A wideband click stimulus of 100 dB peSPL was delivered while the pressure was automatically swept from +200 to –400 daPa at a medium-level pump speed of 200 daPa/s. WBA values were automatically calculated across frequencies by averaging the click stimulus response over 32 sweeps. Absorbance values at 16 individual frequencies bins, i.e. 1/3rd octave bands, were considered for analysis.

WBA values range from 0.0 to 1.0, with 1 indicating complete absorption of sound energy by the middle ear and 0 indicating total reflection. The Titan IMP/WBT440 module displays WBA across frequencies at two pressure conditions: ambient pressure (0 daPa) and peak pressure. Absorbance values were noted at both peak pressure and ambient pressure conditions extracted from WBA. Preliminary testing (PTA and immittance audiometry) and WBA testing were done on the same day.

Statistical analysis

A non-parametric test was used for analysis because the Shapiro–Wilk test ($p > 0.05$) showed a non-normal distribution of data across frequencies. A Kruskal–Wallis test was used to determine whether or not there was a statistically significant difference between the medians of the three independent groups. Pairwise comparisons of groups were performed using the Mann–Whitney *U*-test. The Wilcoxon signed rank test was used for within-group comparisons to study the difference in absorbance between each group's peak and ambient pressure conditions. A p-value < 0.05 was considered significant for all statistical analyses. Cohen's d was used to measure effect size and identify true significant values [25].

Results

Figure 1 shows the mean WBA pattern measured at peak and ambient pressure.

The normal ear group (Group III) exhibited a bell-shaped absorbance pattern. The mean WBA was lowest at 250 Hz, then increased steeply with increasing frequency to two maxima at 1250 and 2000 Hz and reduced to a minimum at 6000 Hz and above. The central TMP group (Group I) exhibited lower mean absorbance at low and mid frequencies up to 2500 Hz compared with the normal ear group. The absorbances were identical near 4000 Hz and then increased at higher frequencies (5000, 6000, and 8000 Hz) compared to the normal ear group.

Compared with the normal ear group, ears with marginal TMP showed almost similar absorbance levels up to 500 Hz, lower absorbance at mid-frequencies up to 3000 Hz, and higher absorbance at frequencies above 4000 Hz. The WBA pattern of the marginal TMP group displayed three peaks at 600, 4000, and 6000 Hz. The mean, median, and standard deviation of WBA values across frequencies and at both peak and ambient pressures are shown in **Table 1**. The test done under both peak and ambient pressure conditions displayed an almost identical pattern.

The comparison of WBA obtained across groups was performed using the Kruskal–Wallis *H*-test and revealed a significant difference ($p < 0.05$; $df = 1$) between the groups. Subsequently, pairwise comparisons between the groups were made using the Mann–Whitney *U*-test to explore whether significant differences existed between the groups at each frequency. **Table 2** summarises the results of the Mann–Whitney *U*-test.

Significant statistical differences were observed across all frequencies between the normal ear and central TMP groups. There were moderate to large effect sizes at almost all frequencies, except at 3000 Hz in the peak pressure condition and 300 and 400 Hz in the ambient pressure condition. Similarly, between the normal ear and the marginal TMP group, significant statistical differences were observed across all frequencies, except at low frequencies (250 to 500 Hz) in both pressure conditions and 600 Hz in the ambient pressure condition, with moderate to large effect sizes.

Between the central and marginal TMP groups, statistically significant differences were observed at 500, 600, and 5000 Hz in both pressure conditions and at 2000 Hz in the ambient pressure condition. Of these significant differences, moderate to large effect sizes were seen at frequencies at 500 and 600 Hz under both pressure conditions and 2000 Hz under ambient pressure conditions.

The Wilcoxon signed-rank test revealed a significant difference between the pressure conditions in the normal ear group at low frequencies up to 1000 Hz and at mid-frequencies of 2000 and 2500 Hz, with moderate to strong effect sizes. In the central TMP group, a significant difference between peak and ambient pressure was observed only for frequencies from 250 to 500 Hz, 1250 Hz, and 2500 Hz. However, the effect size was too small to be considered as significant. For the marginal TMP, a significant difference with a strong effect size was observed at 800 Hz and from 2000 to 5000 Hz.

Although the current study revealed a significant difference between the pressure conditions, the WBA pattern remained nearly identical in both pressure conditions across all groups. A summary of the Wilcoxon signed rank test is tabulated in **Table 3**.

Discussion

The WBA pattern observed in the normal ear group was smooth, broad, and double-peaked. Individuals with normal TMs exhibited low absorbance at 250 and 8000 Hz, with maxima at 1250 and 2000 Hz. The present study's finding coincides with those of Karuppannan and Barman (2021) [15]. These frequencies reflect where the middle ear's stiffness and mass dominate [26]. Reduced absorbance below 1000 Hz reflects the stiffness-controlled middle ear system, whereas at higher frequencies the middle ear system is mass-dominated; both lead to impedance mismatch and reflection of sound energy. Between 1000 and 3000 Hz, the stiffness and mass components cancel, allowing energy to pass into the middle ear [20].

For both pressure conditions, the central TMP group exhibited lower absorbance values at low and mid-frequencies, with medium values around 2500 Hz and higher absorbance beyond 3000 Hz compared with the normal TM group. These findings are consistent with previous studies [15,17,19], which reported reduced absorbance values in the low and mid-frequency range for ears with TMP. This decreased absorbance may be attributed to the lower ratio of the affected eardrum area to the oval window area and to the buckling effect. Tonndorf and Khanna's (1972) classic study on frequency-specific vibration of the TM [3] revealed that the membrane vibrated cohesively at lower frequencies but that TMP disrupts this normal vibratory pattern, necessitating a larger area for low frequencies. This requirement could lead to decreased absorbance, potentially reduced absorbance at low frequencies.

Contradictory results are also apparent and documented in the literature, with studies reporting increased absorbance at low and mid frequencies in ears with TMP in comparison to individuals with intact TM [20,21,27]. Previous authors with contradictory findings to those displayed here have attributed this phenomenon to an increase in mass within the middle ear caused by TMP, which allows low-frequency energy to easily enter the middle ear [26]. At higher frequencies, there are some inconsistencies between our work and that of previous authors, with some studies reporting normal or near-normal absorbance [27,28] although others, consistent with the current work, see increased absorbance at higher frequencies [15,20,29]. One animal study has found reduced absorbance at higher frequencies [24]. The increased absorbance measured in the current study at higher frequencies can be ascribed to shorter wavelengths easily passing through large TMPs.

To our knowledge, no studies have measured WBA in individuals with marginal TMPs. The present study revealed they had similar absorbance to the normal ear group up to about 500 Hz, low absorbance at mid-frequencies up to 3000 Hz, and higher absorbance at frequencies above 4000 Hz. The WBA pattern of the marginal TMP group displayed three peaks at 600, 4000, and 6000 Hz, together with a dip at 2000 Hz. The rationale behind this can be understood by examining the physiology of sound transmission through the TM. Most participants had marginal TMP in the posterior quadrant. Since the resonant frequency of the posterior quadrant of the TM is approximately 2000 Hz [3], damage to this quadrant can lead to a reduction in sound transmission at 2000 Hz and give a significant decrease in absorbance. Most of the TM responsible for low-frequency transmission remains intact, perhaps accounting for an absorbance pattern similar to that of

Table 1. Descriptive statistics (mean, *SD*, and median) of WBA obtained at peak and ambient pressure conditions in the normal ear group, central TMP group, and marginal TMP group

Pressure condition	Frequency [Hz]	Normal ear group (*n* = 20 ears)			Central TMP (*n* = 65 ears)			Marginal TMP (*n* = 13 ears)		
		Mean	*SD*	Median	Mean	*SD*	Median	Mean	*SD*	Median
Peak pressure	250	0.14	0.14	0.05	0.09	0.09	0.06	0.13	0.12	0.08
	300	0.17	0.17	0.06	0.12	0.13	0.09	0.17	0.17	0.12
	400	0.24	0.24	0.07	0.17	0.16	0.14	0.26	0.26	0.20
	500	0.33	0.32	0.1	0.21	0.18	0.17	0.32	0.24	0.24
	600	0.45	0.44	0.12	0.25	0.21	0.21	0.36	0.21	0.30
	800	0.64	0.66	0.12	0.26	0.24	0.20	0.29	0.25	0.21
	1000	0.76	0.78	0.08	0.28	0.31	0.16	0.28	0.28	0.22
	1250	0.8	0.8	0.07	0.31	0.35	0.10	0.21	0.23	0.16
	1500	0.79	0.8	0.09	0.33	0.36	0.13	0.19	0.22	0.17
	2000	0.83	0.86	0.11	0.34	0.32	0.14	0.19	0.24	0.03
	2500	0.76	0.8	0.18	0.44	0.32	0.24	0.33	0.34	0.23
	3000	0.61	0.61	0.18	0.44	0.28	0.49	0.42	0.25	0.41
	4000	0.37	0.38	0.17	0.56	0.22	0.54	0.52	0.18	0.53
	5000	0.25	0.22	0.11	0.60	0.16	0.57	0.44	0.21	0.54
	6000	0.19	0.18	0.09	0.48	0.19	0.44	0.54	0.22	0.50
	8000	0.2	0.18	0.1	0.44	0.23	0.43	0.37	0.17	0.34
Ambient pressure	250	0.13	0.13	0.04	0.09	0.10	0.07	0.14	0.12	0.14
	300	0.16	0.16	0.05	0.13	0.12	0.10	0.18	0.16	0.17
	400	0.23	0.23	0.07	0.19	0.16	0.16	0.27	0.26	0.20
	500	0.31	0.3	0.09	0.22	0.18	0.20	0.38	0.23	0.29
	600	0.42	0.42	0.12	0.25	0.21	0.20	0.41	0.24	0.32
	800	0.61	0.63	0.11	0.26	0.25	0.16	0.34	0.29	0.20
	1000	0.74	0.73	0.09	0.30	0.32	0.16	0.28	0.28	0.23
	1250	0.79	0.8	0.07	0.34	0.32	0.19	0.20	0.23	0.16
	1500	0.79	0.81	0.09	0.35	0.36	0.28	0.18	0.23	0.17
	2000	0.83	0.88	0.11	0.36	0.36	0.21	0.12	0.20	0.19
	2500	0.76	0.82	0.18	0.45	0.32	0.31	0.24	0.32	0.27
	3000	0.61	0.64	0.17	0.45	0.27	0.47	0.36	0.22	0.34
	4000	0.36	0.38	0.16	0.56	0.21	0.54	0.49	0.17	0.51
	5000	0.25	0.22	0.12	0.61	0.18	0.59	0.43	0.21	0.54
	6000	0.19	0.17	0.1	0.49	0.17	0.47	0.54	0.21	0.48
	8000	0.21	0.21	0.1	0.43	0.17	0.40	0.36	0.16	0.34

Table 2. Pairwise comparison between the groups (Mann–Whitney *U*-test) of WBA obtained between the normal ear, central TMP, and marginal TMP groups, together with effect size at peak and ambient pressure conditions. The bolded font indicates a significant difference with medium to large effect size. Significance levels: $^*p < 0.05$; $^{**}p < 0.01$

Pressure condition	Frequency [Hz]	Normal vs central TMP			Normal vs marginal TMP			Central vs marginal TMP		
		z	*p*	*r*	*z*	*p*	*r*	*z*	*p*	*r*
Peak pressure	250	**3.81**	**< 0.01****	**0.41**	1.43	0.15	0.25	1.06	0.28	0.12
	300	**3.45**	**< 0.01****	**0.37**	0.88	0.37	0.15	1.33	0.18	0.15
	400	**3.33**	**< 0.01****	**0.36**	1.03	0.30	0.18	1.13	0.25	0.12
	500	**4.03**	**< 0.01****	**0.44**	1.62	0.10	0.28	**2.29**	**0.02***	**0.35**
	600	**4.64**	**< 0.01****	**0.51**	**1.95**	**0.05***	**0.34**	**2.15**	**0.03***	**0.34**
	800	**5.14**	**< 0.01****	**0.56**	**3.64**	**< 0.01****	**0.63**	0.23	0.81	0.02
	1000	**4.80**	**< 0.01****	**0.52**	**4.01**	**< 0.01****	**0.70**	0.04	0.96	0.00
	1250	**4.99**	**< 0.01****	**0.54**	**4.76**	**< 0.01****	**0.82**	0.68	0.49	0.07
	1500	**4.47**	**< 0.01****	**0.49**	**4.76**	**< 0.01****	**0.83**	1.12	0.26	0.12
	2000	**5.02**	**< 0.01****	**0.55**	**4.79**	**< 0.01****	**0.83**	1.10	0.27	0.12
	2500	**4.53**	**< 0.01****	**0.49**	**3.13**	**< 0.01****	**0.54**	0.00	0.99	0.00
	3000	2.43	0.01*	0.26	**2.17**	**< 0.01****	**0.38**	0.22	0.82	0.02
	4000	**3.08**	**< 0.01****	**0.33**	**2.26**	**< 0.01****	**0.39**	0.30	0.75	0.03
	5000	**6.29**	**< 0.01****	**0.69**	**2.46**	**0.01***	**0.43**	2.10	0.03*	0.23
	6000	**5.79**	**< 0.01****	**0.63**	**4.38**	**< 0.01****	**0.77**	0.63	0.52	0.07
	8000	**4.36**	**< 0.01****	**0.47**	**2.87**	**< 0.01****	**0.50**	0.76	0.44	0.08
Ambient pressure	250	**2.99**	**< 0.01****	**0.32**	0.51	0.60	0.09	1.35	0.17	0.15
	300	2.39	< 0.01**	0.26	0.11	0.91	0.02	1.34	0.17	0.15
	400	2.06	0.03*	0.22	0.33	0.74	0.03	0.99	0.32	0.11
	500	**3.24**	**< 0.01****	**0.35**	0.24	0.81	0.03	**2.76**	**< 0.01****	**0.31**
	600	**4.43**	**< 0.01****	**0.48**	1.01	0.31	0.18	**2.75**	**< 0.01****	**0.31**
	800	**4.91**	**< 0.01****	**0.53**	**2.80**	**< 0.01****	**0.52**	0.93	0.34	0.10
	1000	**4.44**	**< 0.01****	**0.48**	**4.09**	**< 0.01****	**0.76**	0.04	0.96	0.00
	1250	**4.64**	**< 0.01****	**0.53**	**4.80**	**< 0.01****	**0.83**	1.22	0.21	0.13
	1500	**4.37**	**< 0.01****	**0.47**	**4.77**	**< 0.01****	**0.83**	1.74	0.08	0.19
	2000	**4.94**	**< 0.01****	**0.54**	**4.82**	**< 0.01****	**0.83**	**2.25**	**0.02***	**0.35**
	2500	**4.38**	**< 0.01****	**0.48**	**3.57**	**< 0.01****	**0.62**	1.29	0.19	0.14
	3000	**2.38**	**0.01***	**0.26**	**2.87**	**< 0.01****	**0.50**	1.01	0.31	0.11
	4000	**3.35**	**< 0.01****	**0.36**	**2.04**	**< 0.01****	**0.35**	0.92	0.35	0.10
	5000	**6.09**	**< 0.01****	**0.66**	**2.35**	**0.01***	**0.41**	2.36	0.01*	0.26
	6000	**5.85**	**< 0.01****	**0.64**	**4.31**	**< 0.01****	**0.75**	0.63	0.52	0.07
	8000	**3.88**	**< 0.01****	**0.42**	**2.78**	**< 0.01****	**0.52**	0.65	0.51	0.07

Table 3. Wilcoxon signed rank results, its significant level of WBA, and effect size obtained across frequencies between pressure conditions (peak and ambient) across the groups. The bolded font indicates a significant difference with medium to large effect size. Significance levels: **p* < 0.05; ***p* < 0.01

Frequency [Hz]	Normal ear group			Central TMP group			Marginal TMP group		
	z	*p*	*r*	*z*	*p*	*r*	*z*	*p*	*r*
250	**2.57**	**0.01***	**0.57**	**1.89**	**0.05***	**0.23**	0.71	0.47	0.19
300	**2.57**	**0.01***	**0.57**	**2.13**	**0.03***	**0.26**	0.81	0.41	0.22
400	**1.95**	**0.05***	**0.43**	**1.94**	**0.05***	**0.24**	0.51	0.95	0.14
500	**2.75**	**< 0.01****	**0.61**	**2.40**	**0.01***	**0.29**	1.57	0.11	0.43
600	**2.84**	**< 0.01****	**0.63**	0.80	0.42	0.09	1.24	0.21	0.34
800	**2.93**	**< 0.01****	**0.65**	1.00	0.31	0.12	**2.01**	**0.04***	**0.55**
1000	**2.84**	**< 0.01****	**0.63**	0.46	0.64	0.05	0.30	0.75	0.08
1250	0.05	0.95	0.01	**1.90**	**0.05***	**0.23**	0.59	0.55	0.16
1500	0.96	0.33	0.21	1.07	0.28	0.13	0.85	0.93	0.23
2000	**2.53**	**0.01***	**0.56**	0.31	0.75	0.03	**1.68**	**0.03***	**0.46**
2500	**1.98**	**0.04***	**0.44**	**2.11**	**0.03***	**0.26**	**2.49**	**0.01***	**0.68**
3000	1.6	0.1	0.36	1.59	0.11	0.19	**2.43**	**0.01***	**0.67**
4000	1.3	0.18	0.29	1.09	0.27	0.13	**2.43**	**0.01***	**0.67**
5000	0.49	0.62	0.11	1.36	0.17	0.16	**1.86**	**0.05***	**0.51**
6000	0.89	0.37	0.2	1.70	0.08	0.21	0.05	0.95	0.01
8000	0.89	0.37	0.2	0.35	0.72	0.04	1.07	0.28	0.29

normal ears. Additionally, the absorbance peaks at 4000 and 6000 Hz may be attributed to the complex vibratory pattern of the TM as discussed by Tonndorf and Khanna [3]. Moreover, higher absorbance at high frequencies might be linked to shorter wavelengths, enabling sound energy to pass through the TMP more effectively.

When the central and marginal TMPs are compared, it appears that marginal TMP exhibited greater absorbance at lower frequencies (up to about 1000 Hz). Conversely, central TMP showed greater absorbance at mid and high frequencies (except at 6000 Hz) under both peak and ambient pressure conditions. This difference may be attributed to the intact central portions in individuals with marginal TMP, which are responsible for transmitting lower frequencies. In contrast, greater transmission of higher frequencies in individuals with central TMP might be linked to the shorter wavelengths involved.

The current study also analyzed the difference in WBA between peak and ambient pressure conditions. Generally, the presence of a measurable peak is not commonly observed with a TMP. However, the present study obtained WBA measurements at peak pressure for the TMP group, possibly due to use of a wide-frequency stimulus. Our results align with the findings of other studies [15,17,19].

In the normal ear group, WBA measured at peak pressure was significantly higher at 250 to 1000 Hz compared to ambient pressure, while no difference was found at high frequencies. These findings are in line with previously reported studies [30,31]. The difference is attributed to the greater mobility of the TM at peak pressure, a condition where maximum energy enters the middle ear [32]. Under ambient pressure conditions, differences in the ear canal and in middle ear pressure can induce either positive or negative pressure, affecting the TM's stiffness and generating larger impedance, leading to reduced absorbance at low frequencies [33,34].

The study's findings on central TMP revealed a significant difference in WBA between the pressure conditions at 250 to 500 Hz and at about 2500 Hz, although there was a small effect size. The difference might be due to the presence of a large TMP. In contrast, individuals with marginal TMP exhibited a significant difference between ambient and peak pressure conditions at 800 Hz and 2000 to 5000 Hz, with medium to large effect sizes. This difference in pressure conditions may be due to factors such as TMP size and the point of contact between the TM and the sulcus in marginal TMP.

Conclusion

This study demonstrates the effectiveness of WBA in distinguishing between central and marginal TMP. The observed distinct WBA patterns among different types of TMP highlight its potential as a valuable diagnostic tool in clinical settings. Furthermore, the study's outcomes point to possible reasons behind the contradictory findings in previous studies, suggesting the need for more stringent subject selection criteria. Furthermore, the study underscores the importance of TMP types and highlights the need for further investigation into the size and precise location of perforations within specific quadrants, although it did not address size variations within TMP groups.

Disclosure statement

There are no potential conflicts of interest.

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