Wideband Absorbance in Ears with Retraction Pockets and Cholesteatomas: A Preliminary Study

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Abstract

Objectives The objective of this study was to describe wideband absorbance (WBA) findings in patients with cholesteatomas and retraction pockets (RPs).

Design In this prospective study, tympanometry, audiometry, and wideband tympanometry (WBT) were performed on 27 ears with an RP (eight with epitympanic RP and 19 ears with mesotympanic RP), 39 ears with a cholesteatoma (23 ears with epitympanic and 16 ears with mesotympanic cholesteatomas [MCs]), and 49 healthy ears serving as controls.

Results Mean WBA at ambient pressure (WBA_{amb}) of both experimental groups was reduced significantly between 0.8 and 5 kHz relative to the control group. The difference between mean WBA_{amb} and mean WBA at tympanometric peak pressure (WBA_{TPP}) was greater for the RP (0.12–0.16 between 0.5 and 1.5 kHz) than for the cholesteatoma group (0.03–0.11 between 0.6 and 3 kHz). Mean WBA_{amb} of both epitympanic RP (ERP) and epitympanic cholesteatoma (EC) subgroups was significantly lower than that of the control group. Mean WBA_{TPP} of the ERP subgroup attained normal levels as per the control group, while mean WBA_{TPP} of EC subgroup was significantly lower than that of the control group at 0.8 to 1.5 kHz and 4 to 5 kHz. In contrast, both mesotympanic RP and MC subgroups demonstrated similar mean WBA_{amb} and WBA_{TPP} values. No significant differences in WBA_{amb} and WBA_{TPP} results between the RP and cholesteatomas groups were observed. Receiver operating characteristic (ROC) analyses indicated that the area under the ROC curve for distinguishing between the RP and cholesteatomas groups ranged from 0.44 to 0.60, indicating low accuracy in separating the two groups.

Conclusion While it is not possible to distinguish between the RP and cholesteatomas groups based on the WBA_{amb} and WBA_{TPP} results, it is potentially feasible to differentiate between the EC and ERP conditions. Further study using a large clinical sample is recommended to determine the sensitivity and specificity of the WBA test to identify the EC and ERP conditions.

Keywords
- wideband absorbance
- wideband tympanometry
- cholesteatoma
- retraction pockets
- conductive hearing loss

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Retraction of the tympanic membrane is caused by a difference in pressure between the outer ear and middle ear. Retraction pocket (RP) is a special condition, wherein part of the tympanic membrane is stretched in more than the rest of the tympanic membrane, forming a distinct second (or multiple) concavity.[1] An RP is a pathological invagination of the tympanic membrane into the middle ear space[2] that results in a loss of the fibrous layer of the tympanic membrane and the inability of the tympanic membrane to return to its original strength and position. A chronic RP can form adhesions with surrounding structures and accumulation of debris and epithelium, predisposing to the development of cholesteatoma.[3–5]

Longstanding Eustachian tube dysfunction has been linked to the formation of RPs.[6] Although, RPs can be small and self-cleansing, without any symptoms of hearing loss or otalgia, they can progressively erode the adjacent structures and cause otorrhea, hearing loss, and otalgia.[7] The incidence rate of retractions involving the pars flaccida and pars tensa of the tympanic membrane is reported to be 11.23%.[8]

A cholesteatoma is a well demarcated noncancerous cystic lesion derived from the growth of keratinizing squamous epithelium that originates from the external layer of the tympanic membrane or ear canal.[9] Cholesteatoma invades the middle ear cleft and is the most common destructive disease of the ear, affecting both adults and children alike.[10] The annual incidence of acquired cholesteatoma ranges from approximately 9 to 12.6 cases per 100,000 adults and from 3 to 15 cases per 100,000 children.[11–14] The causes of cholesteatoma are often attributed to recurrent history of otitis media and long standing negative pressure in the ear.[15] Patients with advanced cholesteatomas may experience feeling of fullness in their ears, tinnitus, hearing loss, earache, vertigo, and ear discharge.

Based on the site of lesion, RP and cholesteatomas can be classified as (1) epitympanic—arising from the pars flaccida and progressing upward (2) mesotympanic—arising from the pars tensa and progressing medially along the lenticular process and stapes superstructure. Pathological changes associated with middle ear pathologies vary depending on the nature of the disease and site of lesion, and the management of the disease by an otolaryngologist also differs depending on the severity of the disease.

Unfortunately, current standard tests including 226-Hz tympanometry and audiometry fail to detect RP and cholesteatoma with accuracy, resulting in delayed diagnosis and treatment.[16] Hunter and Margolis[17] reported a single case study of early cholesteatoma wherein serial audiograms and tympanograms were normal but videotoscopy showed RP filled with debris. Researchers examining the influence of RPs on the shape and peak of the tympanograms using a middle ear modelling technique have concluded that tympanometry is not a suitable test for RPs.[18] As tympanometry fails to detect RPs and cholesteatomas with high accuracy, an alternative test that can improve the accuracy of detection of these middle ear conditions is deemed necessary.[17] To date, there are no reported studies that have compared tympanometric and audiometric findings in ears with RPs and cholesteatomas.

Wideband absorbance (WBA) is an emerging test that is reported to be sensitive to detecting middle ear disorders in children and adults. WBA, measured at ambient pressure (WBA) or under pressurized conditions (wideband tympanometry, WBT) performs better than the single frequency tympanometry in identifying middle ear pathologies such as otosclerosis, otitis media with effusion (OME), and eustachian tube dysfunction.[12,19–22] To date, there are no studies that have systematically investigated WBA or WBT in ears with RPs or cholesteatomas. As a sensitive measure of middle ear function, WBA may shed light on specific pathological changes of RPs and cholesteatomas. An understanding of WBA findings would aid in better detection and management of RPs and cholesteatomas. The objective of the present study was to describe and compare WBA and WBT findings in ears with RPs and cholesteatomas.

Materials and Methods

Participants

Details of subjects including the age groups are provided in ►**Table 1**. Inclusion criteria for the control group were (1) normal otoscopy findings and aerated middle ear; (2) negative history of middle ear infections at the time of testing; (3) type A tympanogram with tympanometric peak pressure (TPP) between +50 and −100 daPa and peak compensated admittance (Y_{tm}) between 0.3 and 1.6 mmho[23]; (4) air conduction thresholds below 20 dB HL between 0.25 and 8 kHz; (5) air–bone gap (ABG) of less than l5 dB at frequencies between 0.25 and 4 kHz.

The experimental groups consisted of 27 ears from 23 patients with RPs and 39 ears from 37 patients with cholesteatomas who were referred to the Audiology clinic at the Townsville Hospital, Queensland. Diagnosis of RP or cholesteatoma was made by an experienced otolaryngologist. In the RP group, all patients had otomicroscopic and otoendoscopic examinations (using a fiberoptic endoscope to diagnose middle ear conditions), 33% had confirmation of RP through computed tomography (CT) scan and surgery and 4% had confirmation through CT scan only. Of the 10 (37%) patients with RP who had confirmation of RP either via CT scan or surgery, one patient had epitympanic RP (ERP) while nine patients had mesotympanic RP (MRP). About 80% of patients in the RP group had a history of Eustachian tube dysfunction and/or middle ear infection and 17% (4/23) of patients had a history of previous grommet insertions. Only one patient had a grommet in situ and all the other patients had RPs without tympanic membrane perforations.

In the cholesteatoma group, all patients had otomicroscopy, otoendoscopy, and CT scan, while 95% of patients had confirmation of cholesteatoma through surgery. In the cholesteatoma group, 46% (18/37) of patients had a history of ear infections and 18.9% (7/37) of patients had a history of grommet insertions. Five patients had tympanic membrane perforation and two patients had grommets at the time of testing. None of the patients had a history of surgery for treatment of RPs or cholesteatomas prior to enrolling in this study.

Table 1 Subject details

		C	Combined		Epitympanic		Mesotympanic	
			RP	Chol	RP	Chol	RP	Chol
	Total	49	23	37	7	22	16	15
Subjects	Male	23	11	18	4	12	7	6
	Female	26	12	19	3	10	9	9
	Total	49	27	39	8	23	19	16
Ears	Right	29	13	23	4	12	9	11
	Left	20	14	16	4	11	10	5
	Mean	27	31.1	34.7	26.3	35.7	33.1	33.3
Age (in years)	SD	18.1	23.4	21.2	27.2	22	22	20.5
	Range	6.0–59.1	5.1–75.1	6.1–77.1	16.1–75.1	6.1–77.1	5.1–65.1	6.1–77.1
Age group (in years)	5–10	13	7	7	3	4	4	3
	11–20	11	2	5	1	3	1	2
	21–30	3	5	3	1	1	4	2
	31–40	6	2	7	–	4	2	1
	41–50	11	2	5	–	4	2	1
	51–60	5	–	6	–	2	–	4
	61–70	–	4	–	1	–	3	–
	71–80	–	1	4	1	3	–	1

Abbreviations: C, control group; Chol, cholesteatoma; RP, retraction pocket.

RPs and cholesteatomas were further classified as ERP and epitympanic cholesteatoma (EC)—arising from the pars flaccida and growing upward, MRP and mesotympanic cholesteatoma (MC)—arising from the pars tensa and growing medially along the lenticular process and stapes superstructure. Pathological changes in RP and cholesteatoma vary depending on the site of lesion. From a medical perspective, the epitympanic and mesotympanic subgroups indicate the severity of the disease. The management of the disease by an otolaryngologist differs depending on the site of lesion. Hence, apart from analyzing RP and cholesteatoma, the results were also analyzed based on the site of lesion. The first column in ►**Table 1** illustrates the data for all the participants while second and third columns are separated into subgroups.

Procedures

Tympanometry, WBA assessment, and pure tone audiometry were performed in the same order by experienced clinical audiologists. Tympanometry was performed using the Interacoustics Titan version 3.1 (IMP440, Denmark). TPP and Y_{tm} were recorded by sweeping a 226-Hz probe tone from +200 to −400 daPa in a positive to negative sweep direction.

Pure tone audiometry was conducted in a sound-treated room with ambient noise below 30 dBA. An AC-40 clinical audiometer (Interacoustics, Middelfart, Denmark) with TDH-39 earphones was used. Hearing thresholds for air conduction audiometry were determined for octave frequencies between 0.25 and 8 kHz, while bone conduction thresholds were determined for octave frequencies between 0.25 and 4 kHz.

A research version of the Titan software with module (IMP440/WBT440) was used for WBA measurements. An appropriate sized probe was placed in the ear canal and the testing began when the probe light turned green, suggesting an adequate seal for testing. To measure WBA at ambient pressure (WBA_{amb}), click stimuli were presented at ambient pressure at 100 dB peSPL (65 dB nHL) at a rate of 21.5 Hz.[24] For WBT measurements, clicks were presented while ear canal pressure was swept from +200 to −300 daPa at a rate of 200 daPa/s and the TPP was determined from a wideband averaged tympanogram across a frequency range of 0.375 to 2 kHz. Titan automatically generated WBA measured at TPP, and this is denoted as WBA at tympanometric peak pressure ($WBA_{TPP)}$ in this study.

WBA_{amb} and WBA_{TPP} were recorded at 1/24th octave intervals between 0.23 and 8 kHz and then averaged to 16 frequency bands centered at one-third octave frequencies from 0.25 to 8 kHz. Visual inspection of the absorbance results was done to determine adequate probe fit. Absorbance greater than 0.29 in the low frequency band (0.25–-0.5 kHz) was indicative of a probe leak.[25] When probe leakage was suspected, the probe was reinserted, and the test was repeated. The results were saved into a research folder and then exported into excel for further analysis.

Statistical Analysis

Statistical analysis was performed using the IBM SPSS software version 23. A mixed model analysis of variance (ANOVA) was applied to the data wherein group (control, RP, cholesteatoma) served as a between-subject factor, and frequency

(16 levels) and pressure condition (WBA_{amb} and WBA_{TPP}) served as within-subject factor. The Greenhouse and Geisser G-G approach was used to compensate for the violation of compound symmetry and sphericity.[26] Post hoc analyses were performed using multiple pairwise comparison tests with Bonferroni adjustments to determine the frequencies at which significant differences existed between the control and experimental groups.

In view of the small sample size and non-normally distributed data, a Wilcoxon signed rank test was used to compare mean values of WBA_{amb} and WBA_{TPP} of the ERP, EC, MRP, and MC groups. A Mann-Whitney U test was used to analyze the significance of difference in distribution between the control group and the ERP, MRP, EC, and MC groups. A *p*-value of less than 0.05 was considered statistically significant for all analyses.

Receiver operating characteristic (ROC) analysis was used as an objective measure to determine the test performance of WBA to detect RPs and cholesteatomas. Through this ROC analysis, the area under the ROC curve (AROC) was determined.

Results

Results for 226-Hz tympanometry, audiometry, and WBA are presented for the RP and cholesteatoma groups which were subdivided into epitympanic and mesotympanic subgroups.

Tympanometry

Tympanometry results are provided in ►**Table 2**. The tympanograms were classified as: (1) type A with TPP between +50 and −100 daPa and Y_{tm} between 0.3 and 1.6 mmho, (2) type As if the TPP was between +50 and −100 daPa, but Y_{tm} was below 0.3 mmho, (3) type Ad if the TPP was between +50 and −100 daPa, but Y_{tm} was above 1.6 mmho, (4) type B with no identifiable peak, (5) type C with TPP below −100 daPa and Y_{tm} between 0.3 and 1.6 mmho, (6) type Cs if the TPP was below −100 daPa and Y_{tm} was below 0.3 mmho, (7) type Cd if the TPP was below −100 daPa, but Y_{tm} was greater than 1.6 mmho. All 49 ears in the control group had type A tympanograms. In the RP group, 25.9 and 33.3% of ears has type A or Ad and C or Cd tympanograms, respectively, while 40.8% of ears had B type tympanograms. In the cholesteatoma group, 7.7% of ears each had type A or Ad, and C or Cs tympanograms, while 84.6% of ears had type B tympanograms.

The ERP group demonstrated greater prevalence of A and C type tympanograms compared with the EC group. However, 95.6% of ears with EC and 12.5% of ears with ERP had B type tympanograms. Furthermore, 68.8% of ears with MC and 52.6% of ears with MRP had B type tympanograms.

As shown in ►**Table 2**, when compared with the control group, mean Y_{tm} was higher in the RP group and lower in the cholesteatoma group. An ANOVA was performed with Y_{tm} as a dependent variable and group as the between-group factor. Results revealed a significant difference in Y_{tm} among the three groups [F (2, 112) = 10.39, $p = 0.001$, $\eta p^2 = 0.16$]. Post hoc analysis with Bonferroni adjustments revealed a significant difference in Y_{tm} between the control and cholesteatoma groups ($p < 0.01$) and between the RP and cholesteatoma groups ($p = 0.01$). There was no significant difference in mean Y_{tm} between the control and RP groups.

Further as illustrated in ►**Table 2**, mean tympanometric width (TW) of the RP and cholesteatoma groups was also higher than that of the control group. An ANOVA was performed with TW as a dependent variable and group as the between-group factor. Results revealed a significant difference in mean TW among the three groups [F (2, 85) = 26.92, $p = 0.001$, $\eta p^2 = 0.40$]. Post hoc analysis with Bonferroni adjustments revealed a significant difference in mean TW between the control and RP group ($p < 0.01$) and between the control and cholesteatoma groups ($p < 0.01$).

Table 2 Tympanometric results for control group (C) and ears with retraction pocket (RP) and cholesteatoma (Chol)

			Combined		Epitympanic		Mesotympanic	
Measure		C	RP	Chol	RP	Chol	RP	Chol
Type	A	49	7	3	4	–	3	3
	B	–	11	33	1	22	10	11
	C	–	9	3	3	1	6	2
TPP (daPa)	Mean	−19	−130	−124	−106	−128	−142	−120
	SD	27.34	131	93	152	90	121	100
	Range	33 to −90	84 to −343	8 to −307	−21 to −343	8 to −307	−54 to −324	−20 to −277
Static Compliance (mmho)	Mean	0.82	1.18	0.62	0.9	0.23	1.33	0.97
	SD	0.54	0.8	0.62	0.64	0.13	0.86	0.68
	Range	0.31–1.64	0.17–3.02	0.16–2.12	0.19–2.12	0.16–0.55	0.17–3.02	0.16–2.12
Tympanometric width (daPa)	Mean	93	178	245	126	262	202	228
	SD	40	117	99	63	59	130	135
	Range	22–122.4	27–417	65–386	27–220	137–332	46–417	65–386

Abbreviations: SD, standard deviation; TPP, tympanometric peak pressure.

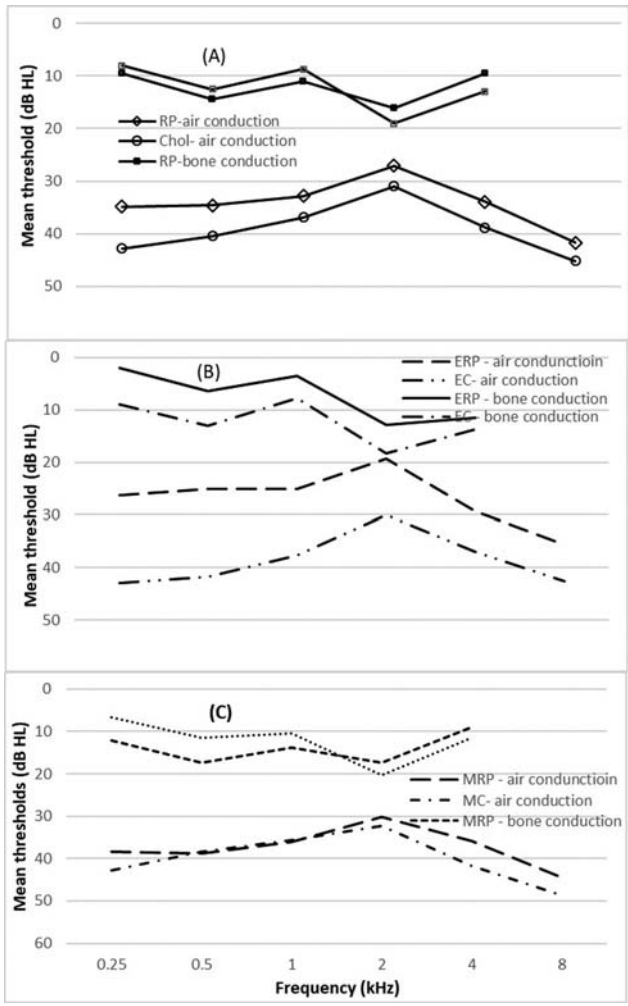

Fig. 1 Mean air–bone gap in control and experimental groups; (**A**) control, retraction pocket, and cholesteatoma; (**B**) control, epitympanic RP, and cholesteatoma; (**C**) control, mesotympanic RP, and cholesteatoma; Error bars indicate ± 1 standard error of mean. RP, retraction pocket.

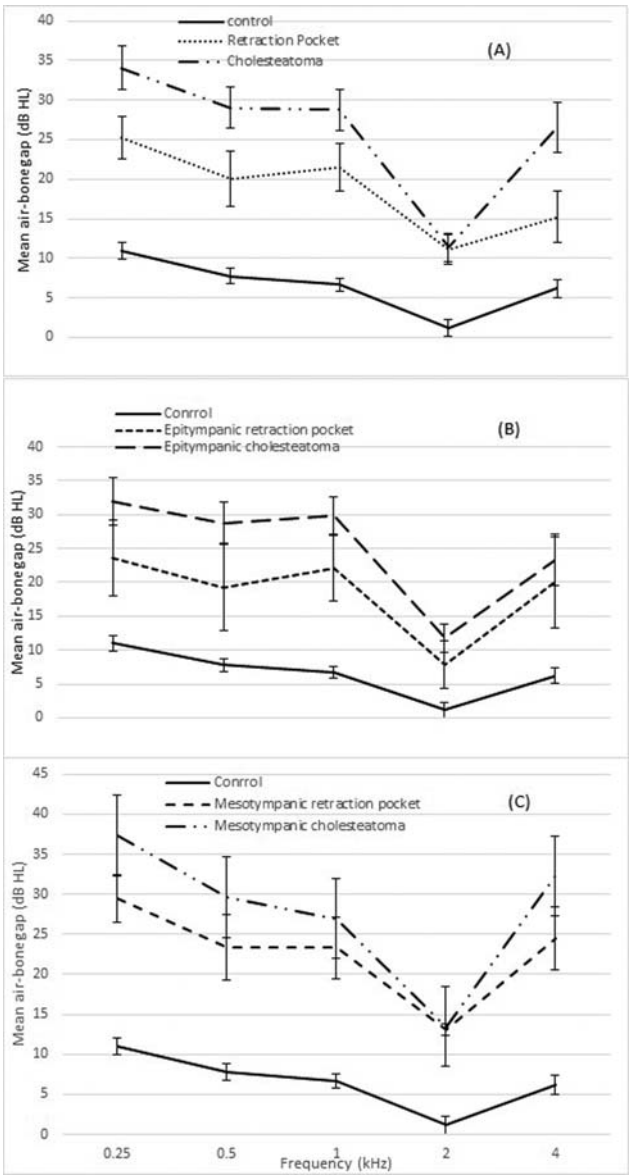

Fig. 2 Mean air–bone gap in control and experimental groups; (**A**) control, retraction pocket, and cholesteatoma; (**B**) control, epitympanic RP, and cholesteatoma; (**C**) control, mesotympanic RP, and cholesteatoma; Error bars indicate ± 1 standard error of mean. RP, retraction pocket.

There was no significant difference in TW between the RP and cholesteatoma groups.

Audiometry

Mean air and bone conduction thresholds for the control group and the cholesteatoma groups are illustrated in ►**Fig. 1**. Mean bone conduction thresholds for the control group were within 10 dB HL, while the mean bone conduction thresholds for the cholesteatoma groups were within 20 dB HL. Air conduction thresholds of the cholesteatoma group were 4 to 8 dB worse than that of the RP group. In comparison, air conduction thresholds of the EC group were 7 to 17 dB worse than that of the ERP group, while air conduction thresholds of the MC group were 0 to 4 dB worse than that of the MRP group.

ABGs for the subjects in each group are presented in ►**Fig. 2**. Mean ABG in the control group was less than 10 dB. In the frequency region between 0.25 and 4 kHz, the RP group demonstrated a mild degree of conductive hearing loss with an average ABG of 11 to 25 dB, while the cholesteatoma group demonstrated a mild to moderate degree of conductive hearing loss with an average ABG of 11 to 34 dB. Repeated measures ANOVA with ABG as a dependent variable and group as the between-group factor revealed a significant difference in mean ABG among the three groups [F (2, 108) = 43.20 $p = 0.001$, $\eta p^2 = 0.44$]. Post hoc analysis with Bonferroni adjustments revealed a significant difference in mean ABG between the control and RP group ($p < 0.001$) and between the control and cholesteatoma groups ($p = 0.001$) at octave frequencies between 0.25 and 4 kHz. There was no significant difference in mean ABG between the RP and cholesteatoma groups.

WBA at Ambient Pressure

As illustrated in ►**Fig. 3A**, mean WBA_{amb} of both RP and cholesteatoma groups was reduced between 1 and 5 kHz when compared with the control group. Maximum

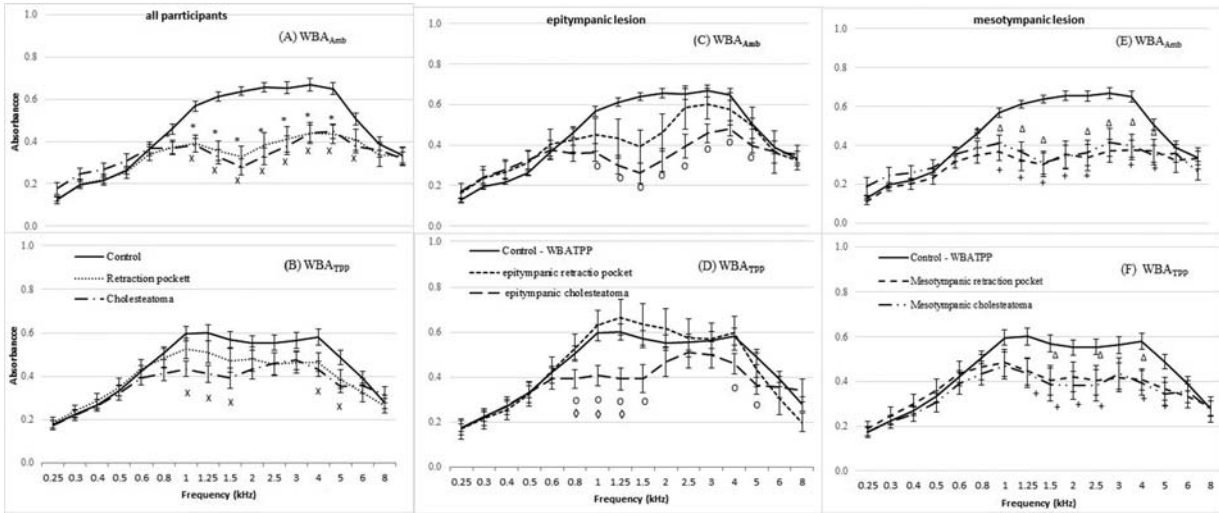

Fig. 3 WBA at ambient and tympanic peak pressures in control and experimental groups. (**A**) WBA_{amb} in all participants in control, retraction pocket and cholesteatoma, (**B**) WBA_{TPP} in all participants in control, retraction pocket and cholesteatoma, (**C**) WBA_{amb} in control, epitympanic retraction pocket and epitympanic cholesteatoma, (**D**) WBA_{TPP} control, epitympanic retraction pocket and epitympanic cholesteatoma, (**E**) WBA_{amb} in control, mesoympanic retraction pocket and mesotympanic cholesteatoma, (**F**) WBA_{TPP} in control, mesotympanic retraction pocket and mesotympanic cholesteatoma.

reductions of 0.31 and 0.36 were observed at 1.5 kHz for the RP group and cholesteatoma group, respectively. Mean WBA_{amb} of cholesteatoma group was 0.01 to 0.05 lower than that of the RP group between 1.25 and 4 kHz.

Results of repeated measures ANOVA revealed a significant group effect [$F(2,112) = 1,747$, $p < 0.01$, $\eta p^2 = 0.24$]. ►**Fig. 3A** shows the frequencies at which the difference in mean WBA_{amb} was significant between the three groups. Mean WBA_{amb} was significantly different between the control and RP groups from 0.8 to 4 kHz and between the control and cholesteatoma groups from 0.8 to 2 kHz and 4 to 5 kHz. There was no significant difference in mean WBA_{amb} between the RP and cholesteatoma groups.

As illustrated in ►**Fig. 3C**, mean WBA_{amb} of the ERP subgroup was 0.07 to 0.25 lower than the control group between 1 and 4 kHz. Mean WBA_{amb} of the EC subgroup was 0.10 to 0.38 lower than the control group between 0.8 and 5 kHz. Mean WBA_{amb} of the EC subgroup showed greater reduction than that of ERP subgroup between 1.5 and 5 kHz. The largest reduction of 0.25 and 0.38 was observed at 1.5 kHz for the ERP and EC subgroups, respectively.

Results of Mann-Whitney U tests applied to the data revealed no significant difference in mean WBA_{amb} between the control and ERP subgroup at any of the frequencies. There was a significant difference in mean WBA_{amb} from 0.8 to 5 kHz between the control and the EC subgroup. There was no significant difference in mean WBA_{amb} between the ERP and EC groups throughout the frequency range from 0.25 to 8 kHz.

As seen in ►**Fig. 3E**, when compared with the control group, mean WBA_{amb} of the MRP group was 0.11 to 0.34 lower between 0.8 and 5 kHz, while mean WBA_{amb} of the MC group was 0.08 to 0.33 lower. Results of Mann-Whitney U tests revealed a significant difference in mean WBA_{amb} between the control and MRP subgroup from 0.8 to 5 kHz, and between the control and MC subgroup from 1 to 5 kHz. There was no significant difference in mean WBA_{amb} between the MRP and MC subgroups.

WBA at TPP

As shown in ►**Fig. 3B**, mean WBA_{TPP} of the RP group was 0.07 to 0.10 lower between 1 and 5 kHz compared with the control group. Mean WBA_{TPP} of the cholesteatoma group was 0.09 to 0.19 lower between 1 and 5 kHz compared with the control group. Mean WBA_{TPP} of the cholesteatoma group was 0.03 to 0.10 lower between 0.8 and 1.5 kHz compared with the RP group.

Results of repeated measures ANOVA revealed a significant group effect [$F\ (2,\ 112) = 3.34$, $p = 0.04$, $\eta p^2 = 0.06$]. Further analysis with Bonferroni adjustments revealed no significant difference in mean WBA_{TPP} between the control and RP groups, and between the RP and cholesteatoma groups at any of the frequencies. However, there was a significant difference in mean WBA_{TPP} between the control and cholesteatoma groups at 0.8, 1, 1.25, 2, 4, and 5 kHz (►**Fig. 3B**).

As seen in the ►**Fig. 3D**, mean WBA_{TPP} of the ERP group was only 0.01 to 0.07 higher between 1 and 4 kHz and 0.08 to 0.09 lower between 6 and 8 kHz compared with the control group. In comparison, mean WBA_{TPP} of the cholesteatoma group was 0.06 to 0.21 lower between 1 and 5 kHz compared with the control group. Mean WBA_{TPP} of the cholesteatoma group was 0.07 to 0.28 lower than the RP group at frequencies between 0.8 and 5 kHz.

Results of a Mann-Whitney U test presented in ►**Fig. 3D**, show that there was no significant difference in mean WBA_{TPP} between the control and ERP groups at any of the frequencies. However, the difference in mean WBA_{TPP} between the control and EC groups was significant at 0.8, 1, 1.25, 1.5, 4, and 5 kHz. There was a significant difference in mean WBA_{TPP} between the ERP and EC subgroups at 0.8, 1, and 1.25 kHz only.

As shown in ►**Fig. 3F**, compared with the control group, mean WBA_{TPP} of the MRP and MC subgroups was 0.12 to 0.18 lower between 1 and 5 kHz. Mean WBA_{TPP} of the MC subgroup was only 0.01 to 0.05 lower than that of the MRP subgroup between 0.25 and 8 kHz. Analysis using Mann-Whitney U tests revealed that the difference in mean WBA_{TPP} between the control and MRP subgroup was significant at 1.25, 1.5, 2.5, and 4 kHz. Similarly, the difference in mean WBA_{TPP} between the control and MC subgroup was significant at 1.25, 1.5, 2, 2.5, 4, and 5 kHz. However, mean WBA_{TPP} of the MRP subgroup was not significantly different from that of the MC subgroup at any frequency.

Comparison between WBA_{amb} and WBA_{TPP}

An ANOVA was performed on WBA data with pressure condition (ambient vs. TPP) as the within group factor and ear condition (control, RP, and cholesteatoma) as between group factor. The results showed that WBA_{TPP} was higher than WBA_{amb} up to 3 kHz for all three ear conditions. The difference between WBA_{amb} and WBA_{TPP} was significantly different between 0.5 and 1.5 kHz for the control, between 0.25 and 1.5 kHz and 4 and 8 kHz for the RP, and between 0.4 and 2.5 kHz except at 1 kHz for the cholesteatoma.

Further, WBA under the pressure conditions was also compared between the epitympanic and mesotympanic subgroups using a Wilcoxon signed rank test. The showed that the difference between WBA_{amb} and WBA_{TPP} was significant from 0.25 to 2 kHz and 4kHz for the ERP group, from 0.8 to 3 kHz for the EC group, from 0.3 to 1.5 kHz and 8 kHz for the MRP group, and from 0.6 to 1 kHz for the MC group.

Additionally, resonance frequency (RF) was obtained from WBA_{TPP} measurements for the RP and cholesteatoma groups. Mean RF of the RP group was 623 Hz (standard deviation = 211 Hz; range = 333–997 Hz), while the mean RF of the cholesteatoma group was 592 Hz (standard deviation = 372 Hz; range = 242–1567 Hz). An ANOVA applied to the RF data revealed no significant difference in RF between the RP and cholesteatoma groups [$F = (1, 42) = 0.74$, $p > 0.05$].

Of the 10 patients who were referred for CT scan or surgery, one patient had ERP while nine patients had MRP. Patients were referred for CT or surgery when the boundaries of the RP were not very clear and cholesteatoma had to be ruled out. WBA_{amb} and WBA_{TPP} of patients with MRP who had confirmation of RP through CT scan or surgery were compared with those diagnosed with MRP by otomicroscopy only. The WBA_{TPP} of patients with confirmation of MRP through CT scan or surgery was only 0.04 to 0.07 higher than the corresponding WBA_{amb} between 1.25 and 2kHz and similar to WBA_{amb} at all other frequencies. In comparison, the WBA_{TPP} of the MRP patients diagnosed through otomicroscopy only was 0.06 to 0.23 higher than the corresponding WBA_{amb}. The difference between WBA_{TPP} and WBA_{amb} in the MRP group diagnosed with otomicroscopy only was highest (0.19–0.23) between 0.5 and 1.25 kHz.

Test Performance

ROC analyses were applied to the WBA data.[27] ROC curves showing test sensitivity against one minus specificity, are standard procedures to evaluate the test performance of a diagnostic test. They show to what extent two distributions (e.g., pass and fail) overlap. The further apart the distributions, greater will be the AROC, which is an overall indication of the diagnostic accuracy of WBA.[28] An AROC value of 1.0 indicates that the test measure reliably distinguishes between two mutually exclusive distributions, for instance, "normal" and "disease" conditions. On the other hand, an AROC value of 0.5 indicates that the predictor is no better than chance to distinguish between the conditions. For the present work, we regard an AROC of at least 0.8 as an acceptable level because AROC < 0.7 is regarded as less accurate and AROC $\geq$ 0.9 is regarded as highly accurate.[29] The 10th percentile of the WBA for the control group was used as the cut off for distinguishing cholesteatomas and RP from healthy ears.

Given this cutoff value for the various measures below which a fail outcome was expected to occur, a comparison with the standard yielded a specific set of hit rate (HR) and false alarm (FA) rate. By varying the WBA cutoff values, many sets of HR and FA rates were determined. A plot of the ROC curve (HR against FA) was obtained for each measure. The point on the ROC curve closest to the top left corner (HR = 1 and FA = 0) was taken as the optimal point to determine the sensitivity and specificity. Furthermore, the AROC was determined for TW and Y_{tm}, and WBA. The cut off values for TW and Y_{tm} were determined based on the American Speech Language Hearing Association guidelines (ASHA).[30] The 10th percentile of the TW and Y_{tm} for the control group was used as the cut off for distinguishing cholesteatomas from healthy ears.

The AROC for Y_{tm} for distinguishing between the control and RP group was 0.60, and between the control and cholesteatoma groups was 0.75. Further, the AROC for distinguishing between the RP and cholesteatoma groups was 0.65.

Similarly, the AROC for TW for distinguishing between the control and RP group was 0.67, and between the control and cholesteatoma groups was 0.83. The AROC for distinguishing between the RP and cholesteatoma groups was 0.66.

The test performance of the WBA test was evaluated at one-third octave frequencies between 0.25 and 8 kHz. The AROC values of WBA_{amb} for distinguishing between control and RP groups ranged between 0.47 and 0.68 across the frequency range. AROC was highest between 1.5 and 2 kHz, with values of 0.64 to 0.68, while AROC values were less than 0.60 below 1.5 kHz and above 2 kHz. The AROC values of WBA_{TPP} for distinguishing between the control and RP groups ranged between 0.48 and 0.55 across the frequency range.

Similarly, the AROC values of WBA_{TPP} for distinguishing between control and cholesteatoma groups ranged between 0.47 and 0.65 across the frequency range with the highest AROC obtained at 1.5 kHz. The AROC values of WBA_{TPP} for distinguishing between the control and cholesteatoma groups ranged between 0.47 and 0.61 across the frequency range. Likewise, the AROC of WBA_{TPP} for distinguishing between RP and cholesteatoma groups ranged between 0.44 and 0.60, while AROC of WBA_{TPP} varied between 0.45 and 0.56.

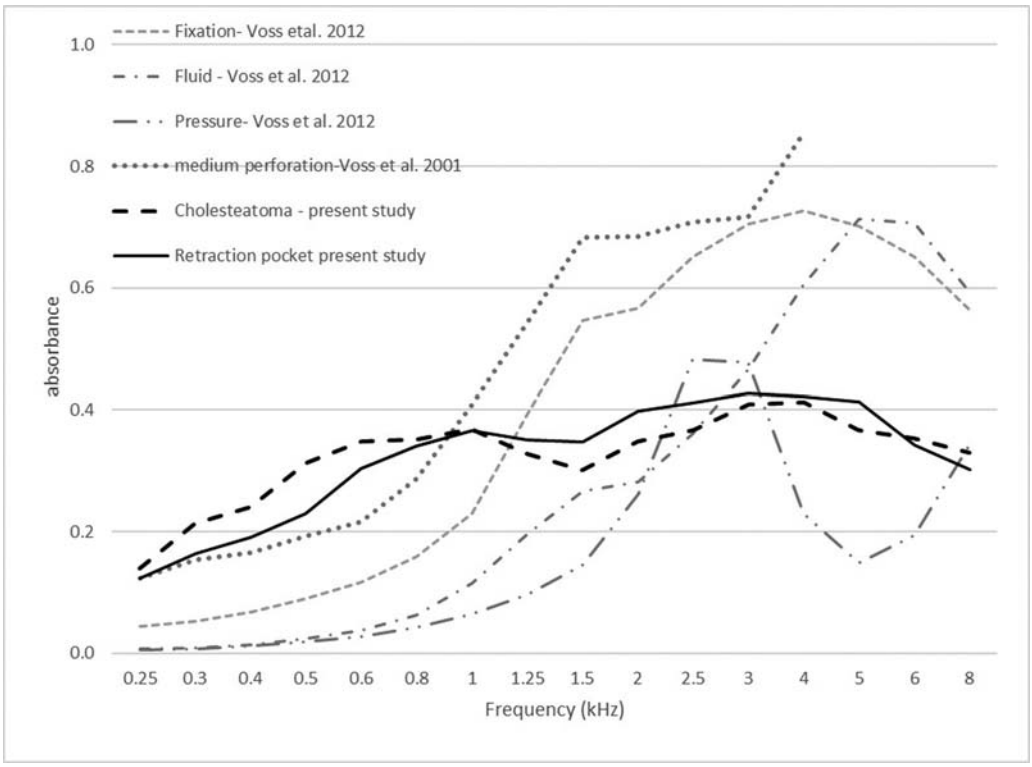

Fig. 4 Comparison of wideband absorbance results at ambient pressure from the present study with various middle ear pathologies from study by Voss et al.[31]

Comparison with Other Middle Ear Pathologies

The results of the present study were compared with the results from other studies that have investigated WBA in ears with middle ear disorders. ►**Fig. 4** compares the WBA results of the present study with that of Voss et al's[31] study on cadaveric ears with ossicular chain dysfunction and fluid in middle ear. The results demonstrated that the results in ears with RP and cholesteatoma were different from the other middle ear disorders. Nevertheless, this is a comparison of the pattern of WBA and further quantitative studies are required to compare the difference between RP, cholesteatoma, and other middle ear disorders.

Discussion

The present study is the first attempt to describe the characteristic WBA findings in patients with RPs and cholesteatomas. The results indicated that both RP and cholesteatoma groups showed slightly different audiometry, tympanometry, and WBA results.

The RP group demonstrated a mild conductive hearing loss, while the cholesteatoma group demonstrated a mild to moderate conductive loss. Nevertheless, there was no significant difference in mean ABG between the two groups. These results hold true regardless of the sites of lesion, indicating that pure tone audiometry findings alone cannot distinguish between RPs and cholesteatomas.

Tympanometry results revealed that the cholesteatoma group had twice the prevalence of type B tympanograms than the RP group. Similar pattern of results was seen with MRP and MC subgroups while ERP and EC subgroups had A, B, and C type tympanograms. Nevertheless, irrespective of the site of lesion, there was no significant difference in Y_{tm}, TW, and RF between the RP and cholesteatoma groups. Further, the test performance of Y_{tm} and TW in distinguishing between RP and cholesteatoma was low. These results suggest that tympanometry alone cannot differentiate between RPs and cholesteatomas.

The RP and cholesteatomas groups showed similar WBA_{amb} and WBA_{TPP} configuration of results, indicating that WBA cannot distinguish between the two middle ear conditions (►**Fig. 2A, B**). Results of ROC analyses also suggested that both WBA_{amb} and WBA_{TPP} cannot differentiate between the RP and cholesteatoma groups. Nevertheless, when the mean WBA_{amb} and WBA_{TPP} were compared within each group, the RP group showed greater WBA_{TPP} than WBA_{amb} between 0.5 and 1.5 kHz, whereas the cholesteatoma group demonstrated an increase in absorbance between 1.5 and 3 kHz. The difference between WBA_{amb} and WBA_{TPP} was slightly higher for the RP group (0.05–0.16) than for the cholesteatoma group (0.03–0.11). This result is probably due to the compensatory pressure effect for the RP patients whose WBA results were more affected by negative middle ear pressures.

When the WBA results were analyzed according to the site of lesion of the RPs and cholesteatomas, differential WBA patterns were observed (►**Fig. 2C–F**). With the epitympanic lesion, both ERP and EC subgroups demonstrated an increase in WBA at TPP relative to ambient pressure between 0.8 and 4 kHz. Mean WBA of the ERP subgroup increased to normal

levels at TPP compared with ambient pressure, while WBA of the EC subgroup remained significantly lower than the control group at frequencies 0.8 to 1.5 kHz and 4 to 5 kHz. In contrast, with the mesotympanic lesion, similar WBA_{amb} and WBA_{TPP} results were obtained for both MRP and MC subgroups.

Changes in middle ear function associated with pathologies vary depending on the nature of the disease and this is reflected in changes in WBA. As illustrated in ►**Fig. 4**, significantly reduced WBA between 0.8 and 5 kHz demonstrated in ears with cholesteatoma and RP in the present study is different from the pattern of WBA reported for other middle ear pathologies. For instance, otosclerosis is associated with reduced WBA at frequencies of 1 kHz and lower.[22,32] Voss et al[31] detailed the effects of various sized perforations on WBA using cadaveric specimens and demonstrated increased absorbance in the low frequencies below 1 kHz for small sized tympanic membrane perforations, and WBA findings similar to that in normal ears at frequencies less than 2.5 kHz for large perforations. Significantly higher absorbance between 0.4 and 1 kHz has been reported in ears with tympanosclerosis.[33,34] Several studies have shown a reduced WBA pattern across the frequency range in ears with OME.[20,33,35] A sharp WBA peak at around 0.4 to 0.8 kHz has been reported in ears with ossicular chain discontinuity,[31–33] while a peak around 1 kHz is reported for ears with superior semicircular canal dehiscence.[32]

Pathological changes associated with the disease process are different for the RP and cholesteatomas conditions. Clinically, RP is associated with a persistent negative middle ear pressure and changes in the structure of the tympanic membrane.[36,37] The process of retraction is accompanied by irreversible changes in the tympanic membrane structure. Hence, the weakened parts of pars tensa come into contact with the underlying ossicles (the long crux of the incus, the incudostapedial articulation). In contrast, pathological changes in cholesteatoma can be due to the presence of the cholesteatoma matrix within the middle ear, erosion of ossicles (through chronic inflammation and pressure necrosis), disruption of the ossicular chain, direct impingement on an intact ossicle, decreased aeration of the middle ear, and reduced vibratory capacity of the tympanic membrane.[38,39]

The ERP group showed the presence of negative middle ear pressure with pathogenesis likely related to the dysfunction of the Eustachian tube, inflammation, and pneumatization of mastoid.[40] Absorbance results of the present study are in agreement with other studies that reported absorbance being reduced at ambient pressure and returning to normal levels at TPP in ears with negative middle ear pressure.[19,41] Using an experimental model, Pau et al[18] reported that tympanometry in ears with RPs or atelectasis does not measure middle ear pressure correctly. The TPP depends on the size of the RP and the remaining gas volume in the middle ear.

In the present study, the RP group exhibited a greater increase in absorbance at TPP compared with ambient pressure than the cholesteatoma group. This suggests that in ears with RP, pressurization of ear canal to TPP increased absorbance of the middle ear. Further, in patients with ERP, absorbance returned to normal levels at TPP. An increase in absorbance at TPP in ears with ERP may suggest an apparently intact middle ear system with tympanic membrane retraction only. Normal absorbance at TPP suggests that normal tympanic membrane mobility could be restored when pressure in the external ear canal is equalized on either side of the tympanic membrane. This may suggest a relatively intact ossicular chain with limited vibratory capacity either due to decreased aeration of the middle ear or decreased vibratory capacity of the tympanic membrane.

In contrast, no such patterns were observed between the MRP and MC subgroups. The audiometric, tympanometric, and WBA patterns of RP and cholesteatoma were similar at ambient pressure and TPP with the mesotympanic site of lesion. While the mechanisms in which MRP and MC affect the middle ear are different, they both involve the middle ear space and ossicular chain. With MRP, it is possible that the mobility of the ossicular chain was also affected as the retracted tympanic membrane drapes over the ossicular chain when it is retracted toward the promontory. The audiological assessment findings of the MC group are influenced by the presence of the cholesteatoma matrix within the middle ear, erosion of ossicles (through chronic inflammation and pressure necrosis), disruption of ossicular chain, direct impingement on an intact ossicle, decreased aeration of the middle ear, and reduced vibratory capacity of the tympanic membrane.[38,39]

The WBA_{TPP} of the patients with MRP who had confirmation of RP through CT scan or surgery was similar to WBA_{amb} across the frequency range except between 1.25 and 2 kHz. In comparison, the WBA_{TPP} of patients diagnosed with MRP with otomicroscopy only was 0.09 to 0.23 higher than $WBA_{amb.}$ One possible reason for this could be that the severity of the condition was different between the two subgroups. The MRP of patients with CT scan or surgical confirmation had either stage SADE III or IV retractions while the patients diagnosed with otomicroscopy only ranged from stage SADE I to IV retraction.[4] Therefore, instead of describing the WBA in MRP as a single group, further research is needed to explore the patterns of WBA based on staging of the RP.

Differentiating between ERP and EC has implications on the management. Some ears with ERP heal spontaneously, while others continue to advance to the EC condition. Although ECs are always managed surgically, the decision on the procedure to be used in the treatment of ERP depends on the functional and anatomical condition of the ear.[2] The difficulties in decision making about surgical treatment of ERP are also related to the fact that the symptoms in ERP can be minimal in both early and advanced stages of the condition. While the decision about surgical management of the ERP is not difficult in patients with significant conductive hearing loss, it can be difficult in ERP patients with a lesser degree of hearing loss. With patients wherein a "wait and see" approach is recommended, WBA can be used to monitor the middle ear condition and alert the clinician to changes in the middle ear status and hence warrant further investigation and management.

Limitations

Although the present study has demonstrated different patterns of WBA in ears with RP and cholesteatoma, there are limitations. First, the sample size was small. Further, both pediatric and adult participants with an age range of 5 to 77 years were included in the control and experimental groups. Although there are differences in WBA due to developmental effects, these differences are too small to be of clinical significance.[42] Second, although the acoustic measures are dependent on the status of the middle ear ossicles, staging of each ossicle was not considered in the present study. Staging of ossicular chain can be used to quantify the extent of erosion of each ossicle. For instance, Martins et al[38] developed a rating scale wherein ratings were assigned to each ossicle as follows: 1 indicates completely normal; 2, cholesteatoma abuts the ossicle but the ossicle is still intact; 3, the ossicle is partially eroded by cholesteatoma; and 4, the ossicle is completely absent (for the malleus and incus) or if the superstructure is eroded (for the stapes). Future studies investigating RP and cholesteatomas need to consider radiological results of staging of each ossicle and relate it to WBA results. Such staging would enable exploring the relationship between ossicular destruction and WBA in detail. Finally, the present study included only one commonly used measure of wideband acoustic immittance, namely, WBA. Further research is needed to incorporate additional immittance measures such as admittance and phase to develop objective measures to improve the identification of RPs and cholesteatomas.

Conclusion

Overall, the present study demonstrated no significant differences in WBA_{amb} and WBA_{TPP} results between RP and cholesteatoma. However, when comparing between the WBA_{amb} and WBA_{TPP} results for each of the subgroups, it may be possible to distinguish between the ERP and EC subgroups, but not between the MRP and MC subgroups. Further research is required to determine the sensitivity and specificity of WBA to differentiate individuals with EC versus those with ERP.

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Conflict of Interest
None.

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