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Original Article

Complementary diagnostic value of tympanometry and tubomanometry in Eustachian tube dysfunction: a retrospective study with serial strategy optimization

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Abstract: Background: Clinical diagnosis of Eustachian tube dysfunction (ETD) lacks an objective gold standard. Tympanometry (assessed by Type Y tympanogram incidence) and tubomanometry (TMM) are widely used, but their comparative diagnostic performance and combined value remain controversial. Objective: To retrospectively evaluate and compare the diagnostic accuracy and agreement of tympanometry and TMM for ETD, using clinical comprehensive diagnosis as the reference, and to explore the clinical utility of serial and parallel diagnostic strategies. Methods: This single-center retrospective study consecutively enrolled 165 patients with ear symptoms who underwent both tests (January 2022-January 2025). Clinical comprehensive diagnosis (blinded to test results) served as the gold standard. Sensitivity, specificity, predictive values, accuracy, area under the ROC curve (AUC), and Cohen's Kappa were calculated. Serial (both tests positive) and parallel (either test positive) strategies were evaluated. Results: ETD was diagnosed in 75/165 patients (45.5%). The AUC for TMM was 0.875 (95% CI: 0.825-0.925), higher than that for tympanometry (0.836, 95% CI: 0.786-0.886), but the difference was not statistically significant (P = 0.375). Tympanometry showed very high sensitivity (0.987) and NPV (0.985) but low specificity (0.711); TMM had higher specificity (0.778) and PPV (0.765). Agreement between the two methods was moderate (Kappa = 0.475, overall agreement 73.9%). Among combined strategies, the serial approach yielded the highest specificity (0.922) and accuracy (0.891), while the parallel approach demonstrated high sensitivity suitable for screening but with low specificity (0.567). Conclusion: Tympanometry and TMM exhibit complementary diagnostic characteristics: tympanometry is an excellent screening tool for ruling out ETD, whereas TMM is more reliable for confirmation. The moderate agreement suggests they capture different pathophysiological dimensions of ETD. The serial strategy optimizes diagnostic specificity and accuracy, supporting its use when confirmation is required.

Keywords: Eustachian tube dysfunction, acoustic impedance, tubomanometry, diagnostic accuracy, consistency

Introduction

Eustachian Tube Dysfunction (ETD) is a common otolaryngological disorder characterized primarily by an imbalance in the Eustachian tube's functions of ventilation, drainage, and protection of the middle ear [1-3]. Patients often present with symptoms such as aural fullness, hearing loss, tinnitus, a sensation of ear blockage, or autophony; significantly impairing their quality of life [4, 5]. ETD is not only a major etiological factor for otitis media with effusion and chronic otitis media but is also closely associated with barotrauma otitis media and tympanic membrane atelectasis [6-8]. Therefore, accurate and objective assessment of Eustachian tube function is of paramount clinical importance for the early diagnosis of ETD, selection of treatment plans, and prognosis evaluation.

However, the clinical diagnosis of ETD has long been challenging. Patient history and symptoms lack specificity, and traditional physical and endoscopic examinations cannot directly and quantitatively assess the dynamic function of the Eustachian tube [9, 10]. Currently, diagnosis often relies on clinicians' empirical and comprehensive judgment, lacking a widely accepted "gold standard". Tubomanometry (TMM),

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as a relatively new technology, measures the pressure required for Eustachian tube opening, providing quantitative indicators of its active opening function. Its objectivity has attracted attention, and it has been gradually applied in both clinical practice and research [11, 12]. On the other hand, tympanometry, particularly the method of assessing Eustachian tube function by observing changes in middle ear pressure during swallowing (e.g., Type Y tympanograms), is a routine examination in both primary care and large hospitals due to the widespread availability of equipment, ease of operation, and non-invasive nature [13, 14]. Both methods aim to evaluate Eustachian tube function but differ in theoretical basis and measurement dimensions: TMM directly measures opening pressure, reflecting the opening resistance of the Eustachian tube, whereas the incidence of Type Y tympanograms in tympanometry indirectly reflects the Eustachian tube's ability to regulate middle ear pressure [15].

Although both methods are clinically utilized, existing research conclusions regarding their relative diagnostic performance and the degree of consistency between their results remain inconsistent. Some studies suggest that TMM has higher specificity and objectivity [16], while others indicate that tympanometry-related indicators have high sensitivity [17]. More importantly, discordant results between the two tests are not uncommon in clinical practice, causing confusion for clinical decision-making. Currently, there is a lack of large-sample studies that systematically compare tympanometry (using the incidence of Type Y tympanograms as the metric) and tubomanometry in diagnosing ETD within the same patient cohort, using a rigorous clinical comprehensive diagnosis as the reference standard. Furthermore, how to leverage the advantages of these two examinations to construct an optimal diagnostic strategy (such as serial or parallel testing) to balance sensitivity and specificity and improve overall diagnostic accuracy is a clinical issue worthy of in-depth exploration.

Therefore, this study aims to conduct a retrospective diagnostic accuracy investigation, using clinical comprehensive diagnosis as the gold standard, to systematically evaluate and compare the diagnostic performance (sensitivity, specificity, predictive values, accuracy, and AUC) of tympanometry (incidence of Type Y tympanograms) and tubomanometry in diagnosing ETD, and to analyze the agreement between the two methods. Simultaneously, this study will further explore the distribution characteristics and correlations of the indicators from these two examinations in different populations and assess the effectiveness of combined serial and parallel diagnostic strategies in enhancing diagnostic performance, with the goal of providing evidence-based guidance for optimizing the ETD diagnostic pathway in clinical practice.

Materials and methods

Study design

This study is a single-center, retrospective, diagnostic accuracy study. It aims to systematically evaluate and compare the diagnostic performance and agreement of tympanometry and tubomanometry in diagnosing Eustachian tube dysfunction, using a clinical comprehensive diagnosis as the reference standard (gold standard), and to explore combined application strategies. The study protocol was reviewed and approved by the Ethics Committee of Affiliated Hospital of Putian University. In light of the retrospective nature of the study and the anonymization of all patient data, the requirement for individual patient informed consent was waived by the Ethics Committee. The design, implementation, and reporting of this study adhered to the principles of the Declaration of Helsinki (2013 revision) and the Standards for Reporting of Diagnostic Accuracy Studies (STARD) guidelines.

Study participants

By querying the hospital information system and the Department of Otolaryngology's specialized examination database, medical records of adult patients who visited due to ear discomfort symptoms and underwent both tympanometry and tubomanometry during the same visit between January 1, 2022, and January 1, 2025, were consecutively included (**Figure 1**).

Inclusion criteria

Ages between 18 and 65 years old.

Chief complaints included at least one symptom suggestive of ETD, such as unilateral or bilateral aural fullness, hearing loss, tinnitus, a sensation of ear blockage, or autophony.

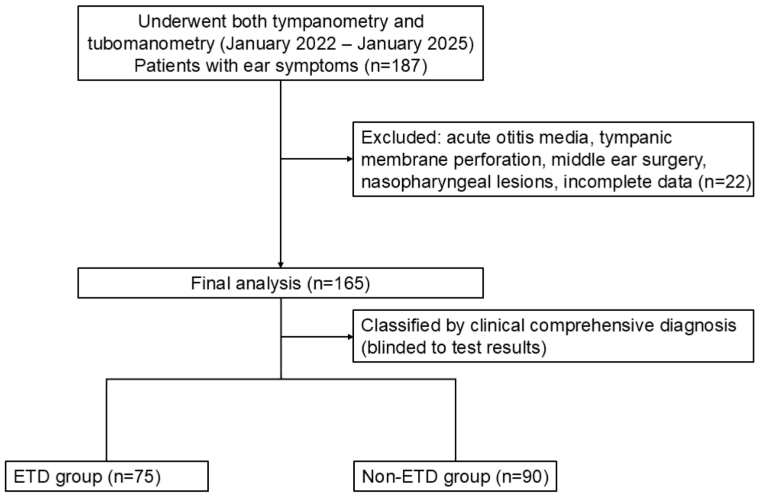

Figure 1. Flowchart of patient selection and study design.

Underwent complete standard tympanometry (including static tympanograms) and tubomanometry during the visit, with original examination reports and data fully accessible.

The medical record documented a clear final diagnosis based on all available clinical information (history, physical examination, audiology, and imaging).

Exclusion criteria

Concomitant acute otitis media or acute upper respiratory tract infection (during the symptomatic period at the time of examination).

Diagnosed with otitis media with effusion but with a disease course of less than 3 months.

Presence of tympanic membrane perforation (any size and location), middle ear cholesteatoma, or history of middle ear surgery (e.g., tympanoplasty, mastoidectomy).

Presence of craniofacial deformities or syndromes that may affect Eustachian tube function (e.g., cleft palate, Down syndrome).

History of nasopharyngeal carcinoma or presence of nasopharyngeal space-occupying lesions found during examination.

Tympanometry or tubomanometry records showed data acquisition failure, severe signal interference, or poor patient cooperation leading to uninterpretable results.

Missing, contradictory, or key clinical data or examination data.

Data collection and definitions

Data were independently extracted from the electronic medical record system by two trained researchers and entered into standardized forms. Discrepancies were resolved through discussion or consultation with a third, senior researcher.

Baseline characteristics

Demographics: Visit date, age, sex.

Clinical features: Chief complaint symptoms, laterality of symptoms, disease duration (in months from symptom onset to the current examination).

Examination methods and metrics

Tympanometry: Equipment and procedure: A GSI TympStar Pro clinical middle ear analyzer was used. Examinations were conducted in a standard soundproof booth. Patients were seated, and the examiner sealed the probe tip in the external auditory canal, sequentially performing 226 Hz probe tone tympanometry. A-type tympanograms (single peak, peak pressure within ± 50 daPa), B-type tympanograms (flat, no peak), and C-type tympanograms (peak pressure below -100 daPa) were recorded.

Key metric: The incidence of Type Y tympanograms was calculated. This metric was determined by instructing patients to swallow multiple times and observing whether the tympanogram displayed a regular "Y" shape change (indicating active Eustachian tube opening). The ratio of the number of swallows producing a Y-shape to the total number of valid swallows was calculated. Based on literature and the laboratory's reference range, a Type Y tympanogram incidence < 0.5 was defined as an abnormal tympanometry result, suggesting Eustachian tube dysfunction.

Tubomanometry: Equipment and Procedure: A TMM01 Eustachian tube function tester was used. Patients were seated and wore a specialized nose clip connected to the device. At three different levels of nasopharyngeal pre-pressure

(45, 50, and 55 daPa), patients were instructed to perform standard swallowing maneuvers (dry swallow or swallow a small amount of water). The device recorded the Eustachian tube opening dynamics during each swallow.

Key metric: The Eustachian tube opening pressure (OP) was recorded, defined as the minimum nasopharyngeal pressure required for successful Eustachian tube opening. The mean value from multiple valid measurements was used as the final OP for the patient. Based on the manufacturer's recommendations and previous studies, an opening pressure > 40 daPa was defined as an abnormal tubomanometry result, suggesting increased Eustachian tube opening resistance.

Other metrics: Eustachian tube closing pressure and pressure equalization success rate were also recorded for auxiliary analysis and correlation studies.

Reference standard (gold standard)

The reference standard for this study was the clinical comprehensive diagnosis. Two senior otolaryngologists, blinded to the specific hypotheses of this study and the results of the tympanometry and tubomanometry (which were hidden prior to analysis), independently reviewed the complete medical records of each patient. This included: detailed history, otolaryngology-specific physical examination (focusing on otoscopic findings), pure-tone audiometry results, and necessary nasopharyngoscopy or temporal bone CT results (if performed). Based on the currently accepted diagnostic consensus for ETD (such as the 7-item ETDQ questionnaire and corresponding symptoms and signs), a comprehensive assessment is made to determine whether the patient has ETD.

If the diagnoses of the two physicians differed, a third, more senior expert was invited to discuss the case until a consensus was reached. Patients were ultimately classified into an ETD group and a non-ETD group.

Statistical analysis

All statistical analyses were performed using SPSS Statistics (version 26.0) and R language (version 4.1.2; packages: pROC, ggplot2, irr). The significance level α was set at 0.05 (two-sided).

Descriptive statistics: Normally distributed continuous data were expressed as mean ± standard deviation, and intergroup comparisons were performed using the independent samples t-test. Non-normally distributed data were expressed as median (interquartile range), and intergroup comparisons were performed using the Mann-Whitney U test. Categorical data were expressed as frequency (percentage), and intergroup comparisons were performed using the chi-square test or Fisher's exact test.

Diagnostic performance evaluation: Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy of tympanometry (using an incidence of Type Y tympanogram < 0.5 as the cutoff) and tubomanometry (using OP > 40 daPa as the cutoff) for diagnosing ETD were calculated. Receiver operating characteristic (ROC) curves were plotted, and the area under the curve (AUC) with its 95% confidence interval was calculated. DeLong's test was used to compare the differences in AUC between the two methods.

Agreement analysis: Cohen's Kappa coefficient was used to assess the agreement between the diagnostic results (positive/negative) of the two examination methods, and the overall agreement rate was calculated. Kappa value interpretation was as follows: < 0.20, slight; 0.21-0.40, fair; 0.41-0.60, moderate; 0.61-0.80, substantial; > 0.81, almost perfect. McNemar's test was used to evaluate whether there was a systematic difference in the positive rates between the two methods.

Combined diagnostic strategies: Two combined diagnostic strategies were evaluated: 1) Serial strategy: Only considered positive if both tests were abnormal; 2) Parallel strategy: Considered positive if either test was abnormal. These strategies were calculated and compared against single tests for diagnostic metrics.

Correlation analysis: Depending on data distribution, Pearson or Spearman correlation analyses were used to explore the correlations between key metrics such as the incidence of Type Y tympanograms, Eustachian tube opening pressure, closing pressure, and pressure equalization success rate, analyzed separately within the ETD and non-ETD groups.

Effect size calculation: For continuous variables with statistically significant intergroup differences, Cohen's d was calculated to quantify the effect size (small: ~0.2; medium: ~0.5; large: ≥ 0.8).

Decision pathway visualization: A decision tree diagram was used to illustrate the diagnostic pathway and patient distribution based on initial triage using tympanometry results, followed by tubomanometry.

Results

Patient baseline characteristics

A total of 165 patients with suspected Eustachian tube dysfunction (ETD) were included in this study. According to the clinical comprehensive diagnostic criteria, 75 patients (45.5%) were diagnosed with ETD, and 90 patients (54.5%) were diagnosed as non-ETD. The patients' ages ranged from 18 to 65 years, with a mean age of 40.06 ± 12.46 years. The mean age of the ETD group (42.81 ± 10.47 years) was significantly older than that of the non-ETD group (37.77 ± 13.53 years) (t = 2.638, P = 0.009). Regarding gender distribution, there were 88 males (53.3%) and 77 females (46.7%), with no significant difference in gender distribution between the two groups (χ^2 = 0.000, P = 1.000). In terms of disease duration, the mean duration in the ETD group was 8.59 ± 5.43 months, significantly longer than the 6.81 ± 4.60 months in the non-ETD group (t = 2.280, P = 0.024). The most common presenting symptoms were aural fullness (45 cases, 27.3%), hearing loss (38 cases, 23.0%), and a combination of aural fullness and hearing loss (28 cases, 17.0%) (**Table 1**).

Comparison of diagnostic performance between the two methods

Using the clinical comprehensive diagnosis as the gold standard, the diagnostic performance of tympanometry (abnormal if incidence of Type Y tympanogram < 0.5) and tubomanometry (abnormal if opening pressure > 40 daPa) is shown in **Figure 2** and Supplementary Table 1. The area under the curve (AUC) for tubomanometry was 0.875 (95% CI: 0.825-0.925), higher than the 0.836 (95% CI: 0.786-0.886) for tympanometry, but the difference was not statistically significant (P = 0.375), suggesting that there was no significant superiority or inferiority in the overall discriminative ability of the two methods. The sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy for tympanometry were 0.987, 0.711, 0.740, 0.985, and 0.836, respectively. For tubomanometry, these values were 0.867, 0.778, 0.765, 0.875, and 0.818, respectively.

Comprehensive comparison of diagnostic performance

A radar chart visually demonstrates the comprehensive performance of the two examination methods across five diagnostic metrics (**Figure 3**). Tympanometry showed relatively balanced performance across metrics, with outstanding sensitivity (0.987) and NPV (0.985). Tubomanometry performed better in terms of specificity (0.778) and PPV (0.765). The accuracy rates of the two methods were similar, at 0.836 and 0.818, respectively.

Consistency analysis between the two methods

The consistency analysis of the diagnostic results of acoustic immittance and tympanogram measurement showed that the Cohen's Kappa coefficient was 0.475, indicating a moderate level of consistency between the two methods (**Figure 4**). The overall consistency rate was 73.9% (122/165 cases), and there were 43 inconsistent cases (26.1%). The McNemar test revealed a difference in the distribution of the two methods at the edge (χ^2 = 4.558, P = 0.033).

Distribution characteristics of tubomanometry opening pressure

The opening pressure in the ETD group (56.6 ± 16.0 daPa) was significantly higher than in the non-ETD group (33.0 ± 14.3 daPa) (t = -9.903, P < 0.001), with an effect size (Cohen's d) of 1.556 (**Figure 5**). Using 40 daPa as the abnormal threshold, 86.7% (65/75) of patients in the ETD group had abnormal opening pressures, compared to only 22.2% (20/90) in the non-ETD group. The median opening pressure in the ETD group was 54.6 daPa (IQR: 45.3-68.3 daPa), compared to 30.4 daPa (IQR: 24.2-38.6 daPa) in the non-ETD group.

Distribution of tympanogram types

The distribution of static tympanogram types differed significantly between the ETD and non-ETD groups (χ^2 = 68.542, P < 0.001) (**Figure 6**).

Table 1. Comparison of patient baseline characteristics

Variable	Total (n = 165)	ETD Group (n = 75)	Non-ETD Group (n = 90)	t/χ^2	*P* value
Age (years)	40.1 ± 12.5	42.8 ± 10.5	37.8 ± 13.5	2.638	0.009
Duration (months)	7.6 ± 5.1	8.6 ± 5.4	6.8 ± 4.6	2.280	0.024
Height (cm)	165.4 ± 8.8	164.7 ± 8.6	166.0 ± 9.0	-0.886	0.377
Weight (kg)	63.0 ± 10.3	62.3 ± 9.8	63.6 ± 10.7	-0.773	0.441
BMI	23.0 ± 2.8	22.9 ± 2.6	23.0 ± 3.0	-0.282	0.779
Gender				0.045	0.831
Male	84 (50.9%)	37 (49.3%)	47 (52.2%)		
Female	81 (49.1%)	38 (50.7%)	43 (47.8%)		
Smoking				0.116	0.734
Yes	43 (26.1%)	21 (28.0%)	22 (24.4%)		
No	122 (73.9%)	54 (72.0%)	68 (75.6%)		
Alcohol				2.488	0.115
Yes	67 (40.6%)	25 (33.3%)	42 (46.7%)		
No	98 (59.4%)	50 (66.7%)	48 (53.3%)		
Hypertension				1.312	0.252
Yes	17 (10.3%)	5 (6.7%)	12 (13.3%)		
No	148 (89.7%)	70 (93.3%)	78 (86.7%)		
Diabetes				0.010	0.921
Yes	8 (4.8%)	3 (4.0%)	5 (5.6%)		
No	157 (95.2%)	72 (96.0%)	85 (94.4%)		
Education level				1.642	0.650
Primary school	31 (18.8%)	11 (14.7%)	20 (22.2%)		
Middle school	61 (37.0%)	30 (40.0%)	31 (34.4%)		
High school	38 (23.0%)	18 (24.0%)	20 (22.2%)		
College or above	35 (21.2%)	16 (21.3%)	19 (21.1%)		
Occupation				3.316	0.345
Manual labor	39 (23.6%)	19 (25.3%)	20 (22.2%)		
Mental labor	71 (43.0%)	29 (38.7%)	42 (46.7%)		
Retired	29 (17.6%)	17 (22.7%)	12 (13.3%)		
Other	26 (15.8%)	10 (13.3%)	16 (17.8%)		
Residence				0.313,	0.576
Urban	94 (57.0%)	45 (60.0%)	49 (54.4%)		
Rural	71 (43.0%)	30 (40.0%)	41 (45.6%)		

Abbreviations: ETD, Eustachian tube dysfunction; BMI, body mass index; M/F, male/female; χ^2, chisquare.

The most common tympanogram type in the ETD group was Type B (46 cases, 61.3%), followed by Type C (19 cases, 25.3%) and Type A (10 cases, 13.3%). In contrast, the non-ETD group was predominantly Type A (69 cases, 76.7%), with relatively fewer Type B (10 cases, 11.1%) and Type C (11 cases, 12.2%) tympanograms.

Correlation analysis of key examination metrics

Correlation analysis of key examination metrics showed that overall, the incidence of Type Y tympanograms was positively correlated with the pressure equalization success rate (r = 0.68, P < 0.001) and negatively correlated with tubomanometry closing pressure (r = -0.40, P < 0.001) (**Figure 7**). In the ETD group, the correlations between these metrics were not significant (P > 0.05). Supplementary Table 2 shows the correlation between the total score of the 7-item questionnaire for Eustachian tube dysfunction (ETDQ-7) and the objective detection indicators. Overall, the ETDQ-7 score was significantly correlated with all four indicators (all P < 0.001). The subgroup analysis results indicated that in the ETD subgroup, the above cor-

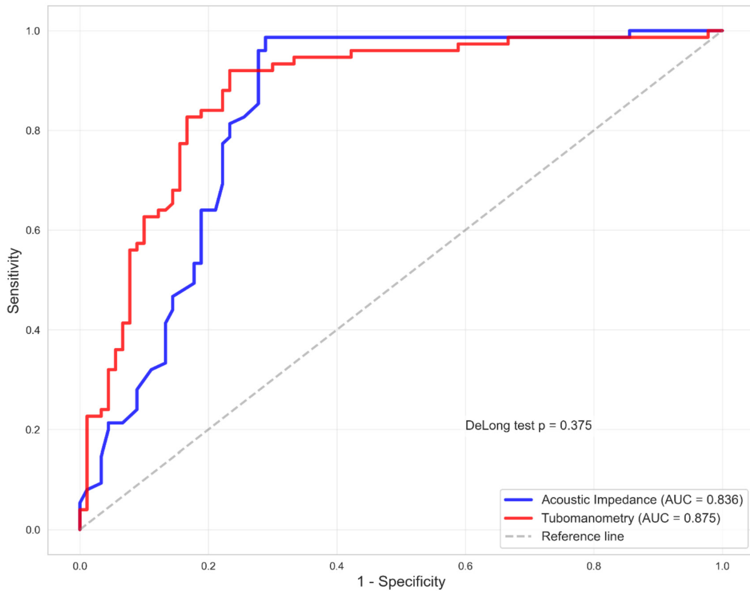

Figure 2. Comparison of ROC curves between acoustic impedance and tubomanometry for ETD diagnosis. Blue curve represents acoustic impedance (AUC = 0.836), red curve represents tubomanometry (AUC = 0.875), dashed line represents reference line. Abbreviations: AUC, area under the curve; CI, confidence interval; ROC, receiver operating characteristic.

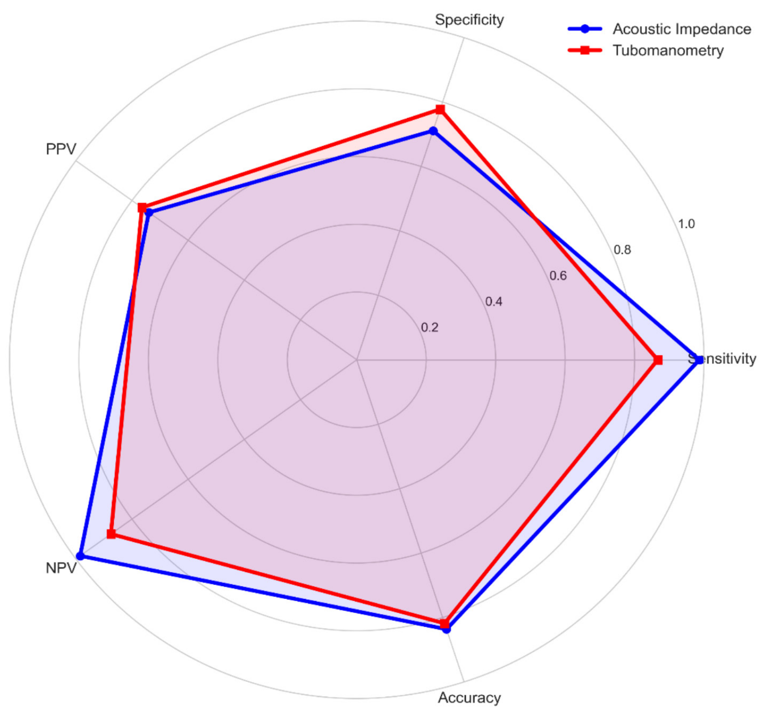

Figure 3. Radar chart of diagnostic performance indicators. Compares comprehensive performance of acoustic impedance and tubomanometry across five dimensions: sensitivity, specificity, PPV, NPV, and accuracy. Abbreviations: PPV, positive predictive value; NPV, negative predictive value.

relation was not statistically significant; this suggests that the severity of symptoms in this population may be determined by factors other than the functional indicators detected in this study.

Analysis of combined diagnostic strategies

The decision curve analysis of the four diagnostic strategies is shown in **Figure 8**. Within the wider threshold probability range (0.2-0.6), the net benefit of the sequential strategy (both tympanometry and Eustachian tube pressure measurement being positive) is higher than that of single tympanometry, single Eustachian tube pressure measurement, and the parallel strategy, indicating that the sequential strategy has the optimal clinical net benefit when high specificity for diagnosis is required. The parallel strategy (either positive) has a slightly higher net benefit in the low threshold probability interval (< 0.2) compared to other strategies, and is suitable for high sensitivity screening. The net benefit of using Eustachian tube pressure measurement alone is overall better than that of using tympanometry alone, which is consistent with the accuracy results of the two (0.818 vs. 0.836).

Discussion

This study retrospectively analyzed 165 patients with suspected ETD, systematically comparing the diagnostic performance of tympanometry (using the incidence of Type Y tympanograms as the metric) and tubomanometry, with the clinical comprehensive diagnosis as the gold standard. The results showed that both methods are valuable for ETD diagnosis, but they possess different advantage characteristics

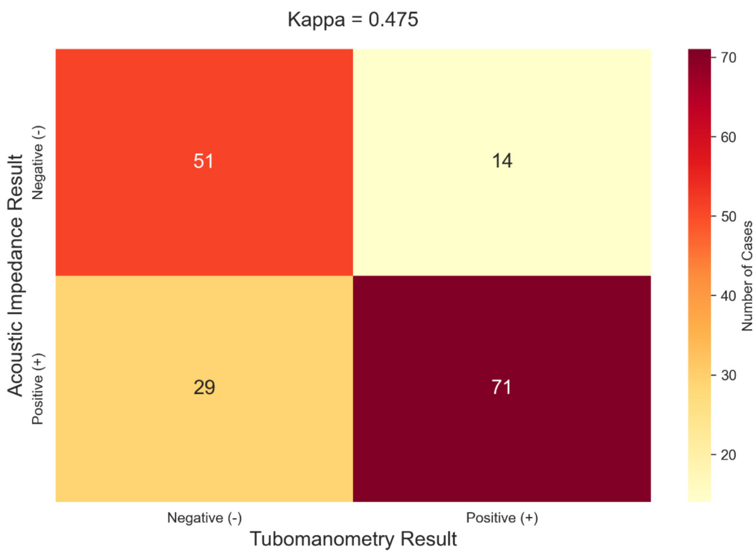

Figure 4. Consistency heatmap of diagnostic results between acoustic impedance and tubomanometry. Show the contingency table distribution of diagnostic results from both tests, with Kappa coefficient of 0.475 and overall agreement rate of 73.9%.

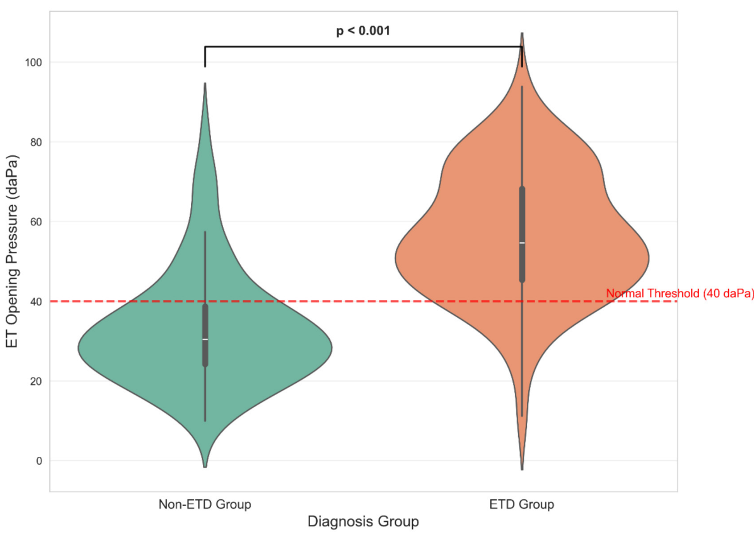

Figure 5. Violin plot of ET opening pressure distribution in ETD and non-ETD patients. Compare ET opening pressure distribution between ETD and non-ETD groups, red dashed line indicates normal threshold (40 daPa), asterisk indicates statistical significance (P < 0.001). Abbreviations: ET, Eustachian tube; daPa, decapascal; IQR, interquartile range.

and only moderate consistency, suggesting potential complementary roles in clinical practice.

Regarding diagnostic performance, this study found that the AUC for tubomanometry (0.875) was higher than that for tympanometry (0.836), but the difference was not statistically significant (P = 0.375). This finding resonates with studies emphasizing the objective quantitative advantages of TMM. However, a deeper analysis of specific metrics reveals clear differences: tympanometry demonstrated near-perfect sensitivity (0.987) and extremely high negative predictive value (NPV) (0.985) [18-20]. This means that if the tympanometry result is normal (incidence of Type Y ≥ 0.5), ETD can be essentially ruled out, highlighting its outstanding value as a screening or exclusion tool. The high sensitivity may stem from the incidence of Type Y tympanograms being sensitive to any slight pressure regulation during swallowing, potentially capturing even partial dysfunction. Conversely, tubomanometry performed better in terms of specificity (0.778) and positive predictive value (PPV) (0.765), indicating a higher confidence level for ETD diagnosis when the opening pressure is abnormally elevated (> 40 daPa). This discrepancy arises from the different principles of the two methods: TMM directly measures the minimum pressure required for active opening, serving as a more direct "resistance" indicator [21, 22], whereas tympanometry reflects the "result" of pressure equalization, which may be influenced by various factors such as middle ear compliance and the duration of tubal opening [23].

The two methods showed only moderate consistency (Kappa = 0.475), and their marginal distributions differed, revealing the common phenomenon of discordant results in clinical practice. The existence of discordant cases (26.1%) may reflect the heterogeneity of ETD pathophysiological types [24-27]. For example, cases positive on tympanometry but negative

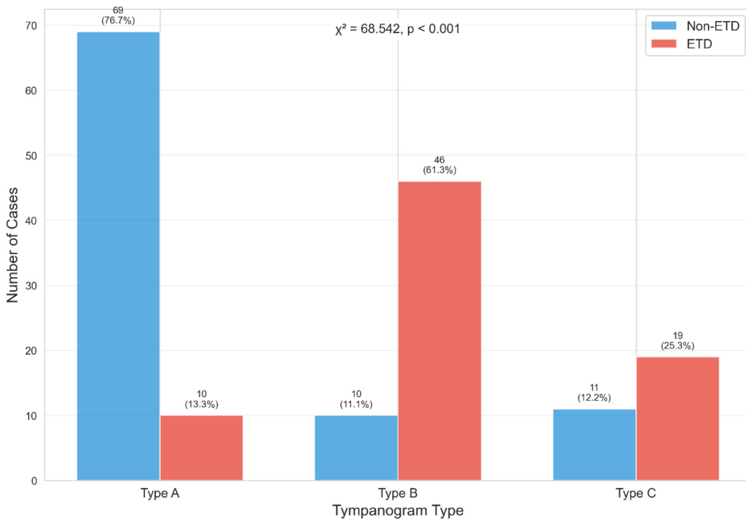

Figure 6. Bar chart of static tympanogram type distribution in ETD and non-ETD patients. Showing distribution differences of Type A, B, and C tympanograms between ETD and non-ETD groups, with case numbers and percentages labeled on bars.

on TMM might suggest mucosal dysfunction (e.g., ciliary dysfunction, mucosal swelling) leading to inefficient pressure equalization, despite no significant increase in mechanical opening resistance. Conversely, cases negative on tympanometry but positive on TMM might occur in early or mild mechanical resistance increase where the pressure regulation capacity is still compensatory, or where swallowing maneuvers were non-standard, affecting the induction of Type Y tympanograms. This underscores the limitations of single tests and the necessity of combining them with clinical assessment [28, 29].

The analysis of tubomanometry opening pressure and tympanogram types in this study provides a basis for understanding ETD pathophysiology. The opening pressure in the ETD group was significantly higher than in the non-ETD group, with a large effect size, strongly supporting that increased opening pressure is a core feature of ETD [30]. Using 40 daPa as the cutoff, 86.7% of patients in the ETD group were abnormal, but 13.3% still had normal opening pressures, suggesting the possible existence of non-"high-resistance" types of ETD, such as patulous Eustachian tube or inadequate closure [31, 32]. The distribution of tympanograms showed that the ETD group was predominantly Type B (61.3%) and Type C (25.3%), consistent with the pathological process of negative middle ear pressure and effusion caused by ETD [33]; in contrast, the non-ETD group was predominantly Type A (76.7%), consistent with a normal middle ear state.

Interestingly, the correlation analysis showed that in the overall population, the incidence of Type Y tympanograms was strongly positively correlated with the pressure equalization success rate and negatively correlated with closing pressure. This indicates a coordinated physiological association among pressure regulation efficiency, opening ability, and closing characteristics in functionally normal Eustachian tubes. However, these correlations disappeared in the ETD group, suggesting that the physiological mechanisms of the Eustachian tube may be uncoupled or disordered in a dysfunctional state, which might serve as a characteristic of ETD [34, 35].

At the level of clinical application strategies, our combined diagnostic analysis provides practical insights. The serial strategy (positive on both) achieved the highest specificity (0.922), PPV (0.901), and overall accuracy (0.891), making it a reliable strategy for confirming ETD, especially suitable for scenarios requiring strict case definitions, such as preoperative assessment or clinical research. In contrast, while the parallel strategy (positive for either) offers high sensitivity suitable for screening, its low specificity (0.567) makes it less suitable for confirmation. For grassroots institutions with limited resources, relying on the highly sensitive tympanometry for initial screening may be an efficient choice; in specialized centers, combining the two methods or adopting a serial strategy can enhance diagnostic precision.

This study has several limitations. First, as a retrospective study, selection bias is possible. All included subjects were symptomatic and had undergone both tests, which might overestimate the performance of the tests in asymptomatic populations or populations with different prevalence rates in the real world. Second,

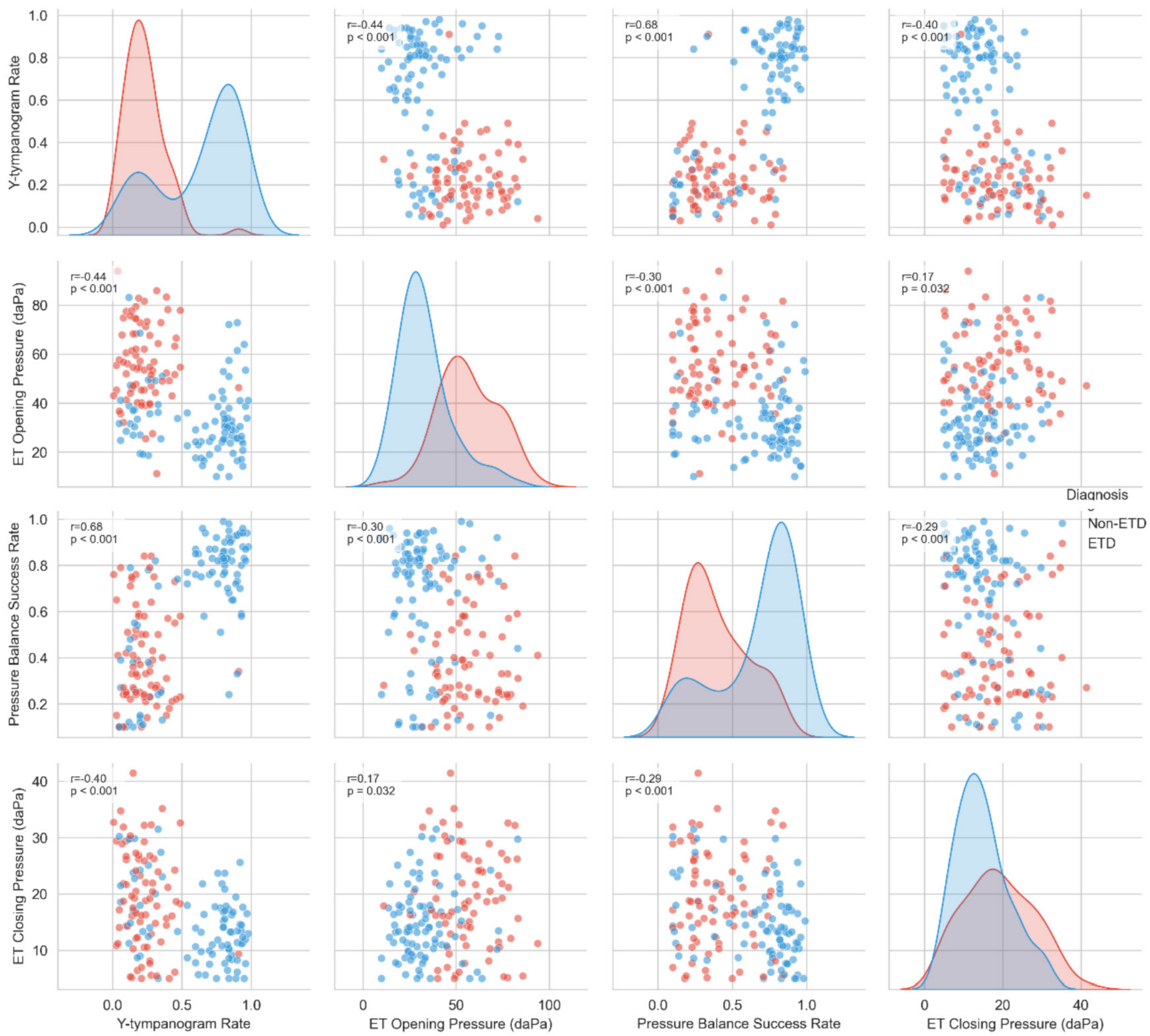

Figure 7. Scatter matrix of key examination parameters. Shows correlations between Y-tympanogram rate, ET opening pressure, pressure balance success rate, and ET closing pressure, colored by ETD diagnosis (blue: non-ETD, red: ETD). Abbreviations: ET, Eustachian tube; daPa, decapascal.

although the "clinical comprehensive diagnosis" used as the gold standard strived for rigor and employed a double-blind assessment, it still contained subjective components and was not an absolute biological gold standard. Third, the abnormal thresholds for tympanometry and tubomanometry in this study (incidence of Type Y < 0.5, OP > 40 daPa) were based on literature and our laboratory's experience; their generalizability needs further validation in different populations. Fourth, this study did not incorporate patient-reported outcome measures such as the Eustachian Tube Dysfunction Questionnaire (ETDQ-7) for symptom correlation analysis; future research could combine these to make the assessment more comprehensive.

In conclusion, tympanometry and tubomanometry are two effective tools for evaluating ETD, each with its own advantages and focus. The incidence of Type Y tympanograms in tympanometry is highly sensitive, making it an excellent exclusion test; tubomanometry has better specificity and is more valuable for confirmation. The moderate consistency between them reveals the heterogeneity of ETD. In clinical practice, the choice of a single or combined diagnostic strategy should be guided by the diagnostic goal (screening or confirmation) and available medical resources. Future prospective research should aim to establish a more precise, multimodal assessment system for Eustachian tube function and explore its asso-

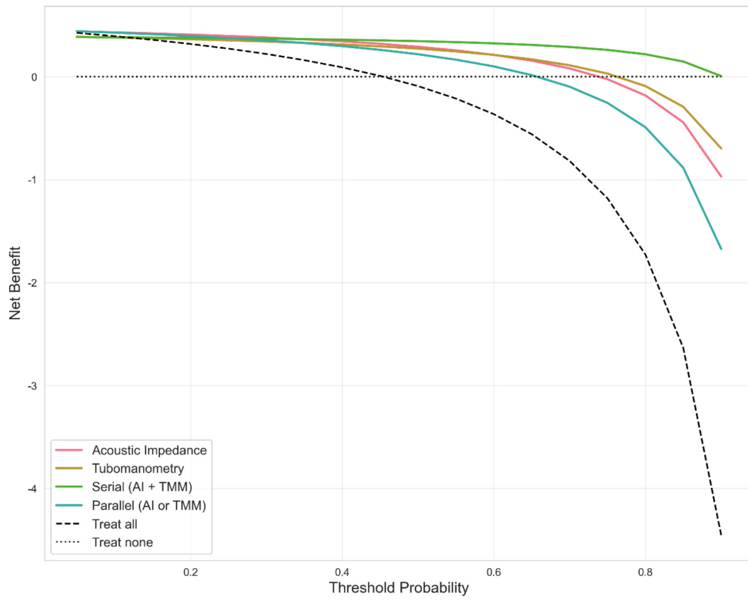

Figure 8. Decision curve analysis for diagnostic strategies of Eustachian tube dysfunction. Abbreviations: DCA, decision curve analysis; TMM, tubomanometry.

ciations with pathological subtypes and treatment responses.

Conclusion

The results of this study indicate that tympanometry (using the incidence of Type Y tympanograms as the metric) and tubomanometry are two effective and complementary methods for evaluating Eustachian tube dysfunction (ETD). Tubomanometry demonstrates higher overall diagnostic performance (AUC 0.875) and specificity, making it a reliable tool for confirming ETD; in contrast, tympanometry exhibits near-perfect sensitivity (0.987) and negative predictive value, making it an excellent screening tool for ruling out ETD. The moderate consistency (Kappa = 0.475) between the two methods reflects the heterogeneity of ETD pathophysiology and suggests that single tests may have limitations. In clinical practice, strategies can be optimized based on the diagnostic goal: the serial strategy (positive on both) yields the highest confidence for confirmation (specificity 0.922) and is suitable for strict diagnostic scenarios, while the parallel strategy (positive for either) offers high sensitivity suitable for screening. Future research should aim to integrate multidimensional functional indicators with clinical symptoms to establish a more precise ETD subtyping diagnostic system.

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Disclosure of conflict of interest

None.

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References

[1] Adams DR, Rowan NR, Lin SY, Pinto JM and Roxbury CR. Are rhinitis and Eustachian tube dysfunction associated in United States adolescents? Int J Pediatr Otorhinolaryngol 2023; 167: 111511.

[2] Agan AD and Perkins NW. Office balloon dilation of the Eustachian tube. Otolaryngol Clin North Am 2025; 58: 601-612.

[3] Al-Hamoud MA, AlShehri MA, Al-Marir AM, Alshahrani AS, Assiri M and FE AL. Outcomes of combined tympanoplasty and Eustachian tuboplasty versus tympanoplasty alone: a systematic review and meta-analysis. Eur Arch Otorhinolaryngol 2025; 282: 5005-5021.

[4] Alper CM, Teixeira MS, Mandel EM and Swarts JD. Dissecting Eustachian tube dysfunction: from phenotypes to endotypes. PLoS One 2023; 18: e0283885.

[5] Bächinger D, Eckhard AH, Röösli C, Veraguth D, Huber A and Dalbert A. Endolymphatic hydrops mimicking obstructive Eustachian tube dysfunction: preliminary experience and literature review. Eur Arch Otorhinolaryngol 2021; 278: 561-565.

[6] Biadsee A, Fanadka F, Dagan O, Firas K and Nageris B. Ostmann's fat pad-does it really matter? Ann Otol Rhinol Laryngol 2021; 130: 173-176.

[7] Boiko NV. Eustachian tube dysfunction: differential diagnosis. Vestn Otorinolaringol 2025; 90: 89-94.

[8] Cayir S, Hizli O, Kayabasi S and Yildirim G. Eustachian tube dysfunction in sleep apnea patients and improvements afforded by continuous positive airway pressure therapy. Braz J Otorhinolaryngol 2021; 87: 333-337.

[9] Chavkin U, Pitaro J, Gavriel H, Taha A, Muallem Kalmovich L, Shilo S, Handzel O, Muhanna N, Warshavsky A, Horowitz G and Ungar OJ. The impact of Eustachian tube function on intratympanic steroid administration. Eur Arch Otorhinolaryngol 2023; 280: 143-149.

[10] Chen T, Shih MC, Edwards TS, Nguyen SA, Meyer TA, Soler ZM and Schlosser RJ. Eustachian tube dysfunction (ETD) in chronic rhinosinusitis with comparison to primary ETD: a systematic review and meta-analysis. Int Forum Allergy Rhinol 2022; 12: 942-951.

[11] Chen X, Tong MCF and Chang WT. A nomogram diagnostic model for Eustachian tube dysfunction in patients with tympanic membrane perforation. J Otolaryngol Head Neck Surg 2024; 53: 19160216241293068.

[12] Cooperman SP, Wong K, Hwa TP and Alyono J. Recidivism and recurrence. Otolaryngol Clin North Am 2025; 58: 177-188.

[13] Dorney I, Otteson T and Kaelber DC. Epidemiology of Eustachian tube dysfunction and related otologic diagnoses among children with achondroplasia. Int J Pediatr Otorhinolaryngol 2022; 163: 111339.

[14] Fontes Lima A, Carvalho Moreira F, Esteves Costa I, Azevedo C, Mar F and Dias L. Nasal septum deviation and Eustachian tube function: a prospective case-control study based on tympanometry, tubomanometry, and ETDQ-7. Acta Otorrinolaringol Esp (Engl Ed) 2022; 73: 35-41.

[15] Grajczyk A, Sobczyk K and Dżaman K. Nasal and Eustachian tube function during menstrual cycle. Otolaryngol Pol 2025; 79: 1-8.

[16] Herrera M, Miranda E, Villarreal I, Crespo T and Plaza G. Assessing the usefulness of tubomanometry as a diagnostic tool in Eustachian tube dysfunction. Eur Arch Otorhinolaryngol 2024; 281: 5135-5143.

[17] Huve FDC, Bauer JA, Selaimen FA, Silva M and Costa SSD. Experimental cholesteatoma: a comparison between spontaneous and induced models. Braz J Otorhinolaryngol 2023; 89: 73-78.

[18] Ikeda R. Diagnosis and treatment of patulous Eustachian tube. Auris Nasus Larynx 2024; 51: 947-955.

[19] Ikeda R, Hamanishi S, Kikuchi T, Oshima H, Kawamura Y, Kusano Y, Kawase T, Katori Y, Wada H and Kobayashi T. Objective assessment of autophony during phonation in the diagnosis of patulous Eustachian tube patients. Auris Nasus Larynx 2021; 48: 738-744.

[20] Kaderbay A, Karkas A, Schmitt D, Mura T, Lavieille JP and Venail F. Balloon dilation for persistent unilateral chronic obstructive Eustachian tube dysfunction is effective: a prospective multicentre study. Eur Arch Otorhinolaryngol 2023; 280: 1101-1109.

[21] Klimek L, Brough HA, Arasi S, Toppila-Salmi S, Bergmann C, Jutel M, Bousquet J, Hox V, Gevaert P, Tomazic PV, Rondón Segovia C, Cingi C, Cuevas M, Gröger M, Huber P, Reitsma S, Rudenko M, Maza-Solano J, Gane S, Karavelia A, van Gerven L, Schiappoli M, Bozkurt B, Becker S, Chaker A, Wollenberg B, Mösges R, Huppertz T, Hagemann J, Palomares O, Bärhold F, Pfaar O, Del Giacco S, Bonadonna P, Moreira A, Agache I, Akdis CA, Fokkens W, Walusiak-Skorupa J, de Las Vecillas L, Alvaro Lozano M, Giovannini M, Untersmayr E, Feleszko W, Cianferoni A, Sahiner UM, Eguiluz-Gracia I, Shamji M and Torres Jaén MJ. Otitis media with effusion (OME) and Eustachian tube dysfunction: the role of allergy and immunity-an EAACI position paper. Allergy 2025; 80: 2429-2441.

[22] Kocoń S, Ziarno R, Skórkiewicz K, Wiatr A and Wiatr M. The variability of function of the Eustachian tube in patients with chronic sinusitis. Otolaryngol Pol 2023; 77: 1-5.

[23] Kourtidis S, Hempel JM, Saravakos P and Preyer S. Diagnostic value of computed tomography in Eustachian tube dysfunction. Auris Nasus Larynx 2022; 49: 352-359.

[24] LaBanc AJ and Schlocker C. Case report: Eustachian tube dysfunction after penetrating facial trauma. Mil Med 2023; 188: e3716-e3719.

[25] Lin JT, Hsu HJ, Ho CY, Tsai SW, Li YL and Wu JL. Balloon dilation Eustachian tuboplasty for dilatory dysfunction with and without effusion: a comprehensive outcome analysis. Otolaryngol Head Neck Surg 2023; 169: 1179-1186.

[26] Lindfors OH, Räisänen-Sokolowski AK, Suvilehto J and Sinkkonen ST. Middle ear barotrauma in diving. Diving Hyperb Med 2021; 51: 44-52.

[27] Liu S, Ni X and Zhang J. Assessment of the Eustachian tube: a review. Eur Arch Otorhinolaryngol 2023; 280: 3915-3920.

[28] Liu YC, Dean M, Thottam PJ, Babu S, Hosek K, Poe D and Mukerji S. Balloon Dilation of the Eustachian Tube (BDET)-a pooled analysis in pediatric patients. Laryngoscope 2025; 135: 4887-4893.

[29] Lu H, Su J, Chi W, Zou T, Yu M and Wang K. Clinical value of the Eustachian Tube Function Scoring System T-ETDQ: a prospective diagnostic study. Eur Arch Otorhinolaryngol 2022; 279: 2223-2230.

[30] Maddineni S and Ahmad I. Updates in Eustachian tube dysfunction. Otolaryngol Clin North Am 2022; 55: 1151-1164.

[31] Mukerji S, Rosas Herrera AM, Rochat R, Hosek K and Liu YC. Outcomes and complications of pediatric Eustachian tube dilation surgery. Otolaryngol Head Neck Surg 2024; 171: 1530-1534.

[32] Nibhanupudy TJ, Patel A, Trinh CP, Jenkins E, Weber PC and Levi JR. Efficacy of intranasal corticosteroid sprays in relieving clinical signs of Eustachian tube dysfunction: a systematic review and meta-analysis of randomised, controlled trials. J Laryngol Otol 2024; 138: 1065-1072.

[33] Mehta NK, Ma C, Nguyen SA, McRackan TR, Meyer TA and Lambert PR. Medical management for Eustachian tube dysfunction in adults: a systematic review and meta-analysis. Laryngoscope 2022; 132: 849-856.

[34] Parsel SM, Unis GD, Souza SS, Bartley H, Bergeron JM, Master AN and McCoul ED. Interpretation of normal and abnormal tympanogram findings in Eustachian tube dysfunction. Otolaryngol Head Neck Surg 2021; 164: 1272-1279.

[35] Quarato A, Di Cianni S, Germano F, Filaferro L, Lo Re F, Manni MS, Magliulo G, Greco A, De Virgilio A, Pace A, Bellizzi MG, Croce E, Gatti L and Iannella G. Eustachian tube dysfunction in professional navy divers workers. Acta Otolaryngol 2025; 145: 800-805.

Supplementary Table 1. Sensitivity analysis of diagnostic thresholds for tympanometry and tubomanometry

Method	Threshold	Sensitivity	Specificity	Accuracy	AUC
Acoustic Impedance	0.4	0.880	0.722	0.794	0.836
Acoustic Impedance	0.5	0.987	0.711	0.836	0.836
Acoustic Impedance	0.6	0.987	0.689	0.824	0.836
Tubomanometry	35	0.947	0.656	0.788	0.875
Tubomanometry	40	0.867	0.778	0.818	0.875
Tubomanometry	45	0.773	0.844	0.812	0.875

Abbreviation: AUC, area under the curve.

Supplementary Table 2. Correlation between ETDQ-7 scores and objective parameters

Group	Parameter	Pearson r	*p*-value
Overall	Y-tympanogram Rate	-0.639	< 0.001
Overall	ET Opening Pressure (daPa)	0.580	< 0.001
Overall	ET Closing Pressure (daPa)	0.254	< 0.001
Overall	Pressure Balance Success Rate	-0.487	< 0.001
ETD Group	Y-tympanogram Rate	0.024	0.840
ETD Group	ET Opening Pressure (daPa)	0.062	0.598
ETD Group	ET Closing Pressure (daPa)	0.032	0.787
ETD Group	Pressure Balance Success Rate	-0.102	0.384
Non-ETD Group	Y-tympanogram Rate	-0.305	0.003
Non-ETD Group	ET Opening Pressure (daPa)	0.133	0.213
Non-ETD Group	ET Closing Pressure (daPa)	0.060	0.572
Non-ETD Group	Pressure Balance Success Rate	-0.160	0.133

Abbreviations: ET, Eustachian tube; daPa, decapascal; ETDQ7, Eustachian Tube Dysfunction Questionnaire7.