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Precision of Lateralization of Bone conduction in Audiometric and Tuning Fork Weber's test in patients with Conductive Hearing Loss.

Dr. S. Swathi[1*], Dr. R.Venkataramanan[1], Dr. Geetha Kishan Siddapur[1], Dr. Ganesh S[1] , Dr. Merwin Paul. R[1], Dr. Abilash PM[1]
[1]Department of E.N.T, Sri Lakshmi Narayana Institute of Medical Sciences, Pondicherry, India

ABSTRACT
Introduction : *Conductive Hearing Loss (CHL) often presents with lateralization of sound to the affected ear , making hearing tests fundamental in clinical settings. Accurate lateralization of bone conduction in both Audiometric Weber's (AW) and Tuning fork Weber's (TFW) tests is crucial in diagnosing the type and severity of hearing loss .*
Methods : *In this observational cross-sectional study ,80 people aged 12-67 years with unilateral CHL or bilateral asymmetrical CHL in the ENT Department , SLIMS, Puducherry were enrolled. The TFW test was performed according to the established protocol at 256 and 512 Hz. For the AW test , bone vibrator was placed in the middle of forehead, where 250 and 500 Hz frequencies were tested. TF and AW test results were compared with the expected lateralisation from the respective PTA results.*
Results: *At 256 Hz , overall accuracy values of TFW and AW tests were 81.1% and 86.5% respectively . At 512 Hz the overall accuracy results of TFW and AW tests were 85.1% and 82.4% respectively.*
Conclusions: *Both AW and TFW tests were reasonably accurate in assessing patients with CHL . As such it is recommended for audiologists to conduct simple AW test in conjunction with other audiological tests to verify PTA results as masking problems and questionable audiograms are commonly encountered in clinical practice.*
Keywords: *Bone conduction , conductive hearing loss, weber's test, lateralisation*

INTRODUCTION

Conductive hearing loss (CHL) often presents with lateralization of sound to the affected ear , making hearing tests fundamental in clinical settings [1]. Accurate lateralization of bone conduction in both audiometric and tuning fork Weber's tests is crucial in diagnosing the type and severity of hearing loss[1,2] . The interpretation of Weber's test results can be challenging due to variations in patient anatomy , bone conduction pathways , and subjective patient responses[3,4]. These factors can lead to inconsistencies in the diagnosis of CHL , particularly in borderline cases[5]. Both audiometric and tuning fork tests are widely used , their precision in lateralizing bone conduction differs[6] . Audiometric tests provide quantifiable data, whereas tuning fork tests rely on qualitative assessment, which may lead to differing diagnostic conclusions[4] . Standardizing the interpretation of Weber's test and improving the precision of bone conduction lateralization are essential for consistent diagnosis and management of CHL[5] Research indicates that discrepancies in test outcomes can lead to misdiagnosis and inappropriate treatment[5,6] . This study aims to determine the precision between the Audiometric Weber (AW) and the Tuning Fork Weber (TFW) test and to compare the TFW and AW results with expected lateralization from the respective PTA results

MATERIAL AND METHODS

Study Design

It was an Observational cross - sectional study.

Study Setting

The participants were recruited from the ENT Department at SLIMS , Puducherry.

Study Subjects

A total of 80 individuals aged between 12 and 47 years with unilateral conductive hearing loss (CHL) or bilateral asymmetrical CHL were enrolled in the study.

METHODS

The Tuning Fork Weber's (TFW) test was conducted using established protocols using tuning forks at 256 Hz and 512 Hz frequencies . The test aimed to determine sound lateralization , which typically localizes to the ear with CHL . For the Audiometric Weber's (AW) Test , a bone vibrator was placed in the middle of the forehead to test bone conduction at frequencies of 250 Hz and 500 Hz . This test is designed to provide quantifiable data . Results from both the TFW and AW tests were compared with the expected lateralization based on Pure Tone Audiometry (PTA) results , which served as the reference standard for assessing hearing threshold. In addition to the primary accuracy analyses, we employed linear mixed effects modeling to account for repeated measures within subjects. The model included test type (TFW vs AW) and frequency as fixed effects, with subject ID as a random effect. We further validated the tests by analyzing performance across different etiologies and severities of conductive hearing loss using stratified analyses.

RESULTS

Demographic Parameters	**Values n=80** (%)
Mean Age (years)	34.5
Gender	
Males	45 (56.3%)
Females	35 (43.7%)
Type of Hearing Loss	
Unilateral CHL	60 (75%)
Bilateral Asymmetrical CHL	20 (25%)
Diagnosis	
Mucosal Chronic Otitis Media	28 (35%)
Middle Ear Effusion	23 (28.75%)
Secretory Otitis Media	13 (16.25%)
Cholesteatoma	11 (13.75%)
Traumatic perforation of Tympanic Membrane	5 (6.25%)

Table 1 shows various baseline characteristics enrolled for the study.

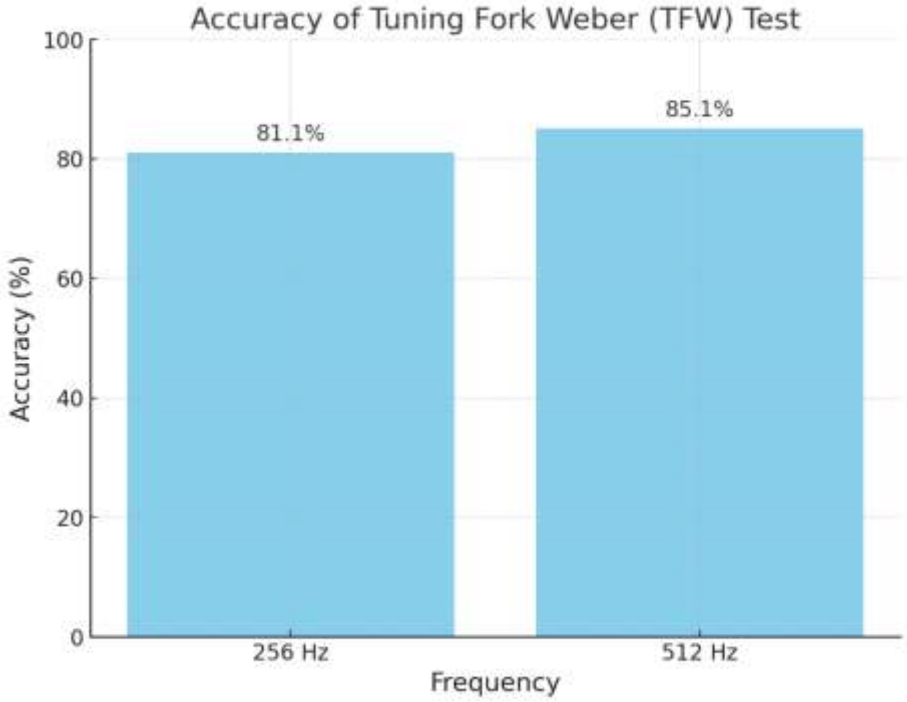


Figure 1 : shows the accuracy of the TFW test at two frequencies : 256 Hz- Accuracy of 81.1% , 512 Hz - Improved accuracy of 85.1% .The chart highlights the increase in accuracy when using a higher frequency.

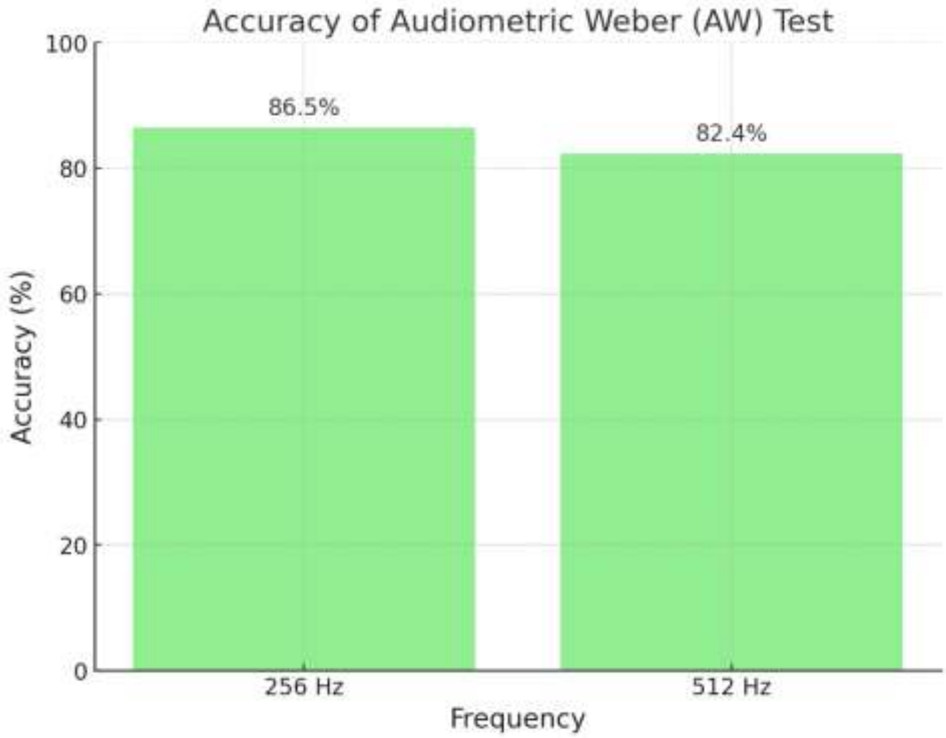


Figure 2 : shows the accuracy of Audiometric Weber (AW) Test at two frequencies :256 Hz : Accuracy of 86.5% , 512 Hz: Slightly lower accuracy of 82.4%. The chart shows that the AW test is more accurate at 256 Hz but less accurate at 512 Hz compared to the TFW test

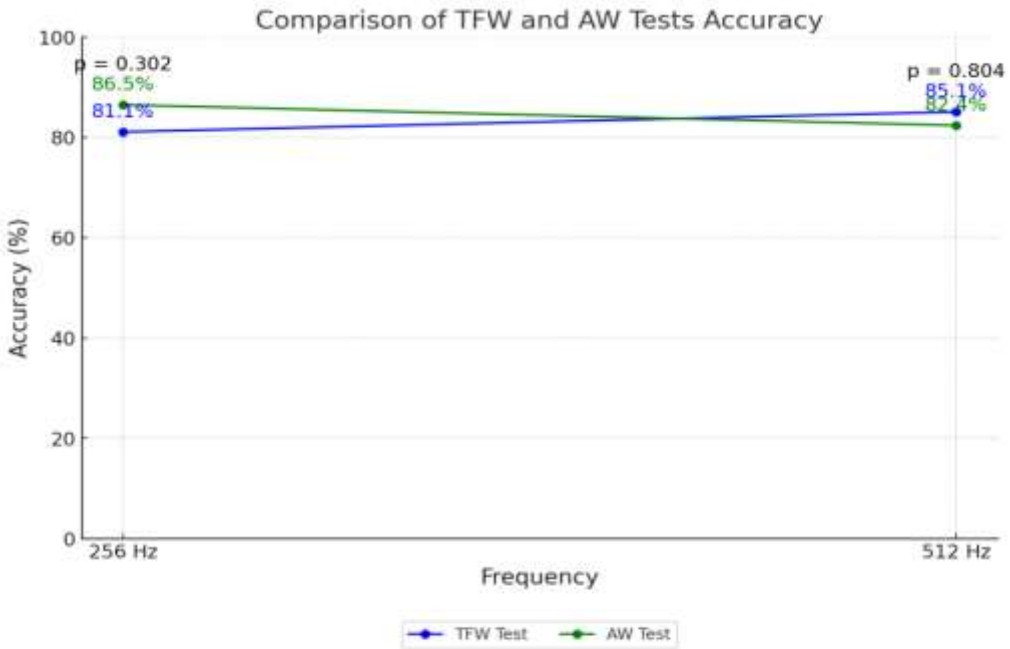


Figure 3 shows comparison of TFW and AW tests at 256Hz and 512Hz : AW test has higher accuracy (86.5%) compared to the TFW test (81.1%) at 256Hz , TFW test has higher accuracy (85.1%) compared to the AW test (82.4%) . The figure indicates p-values to indicate the statistical significance of the differences.

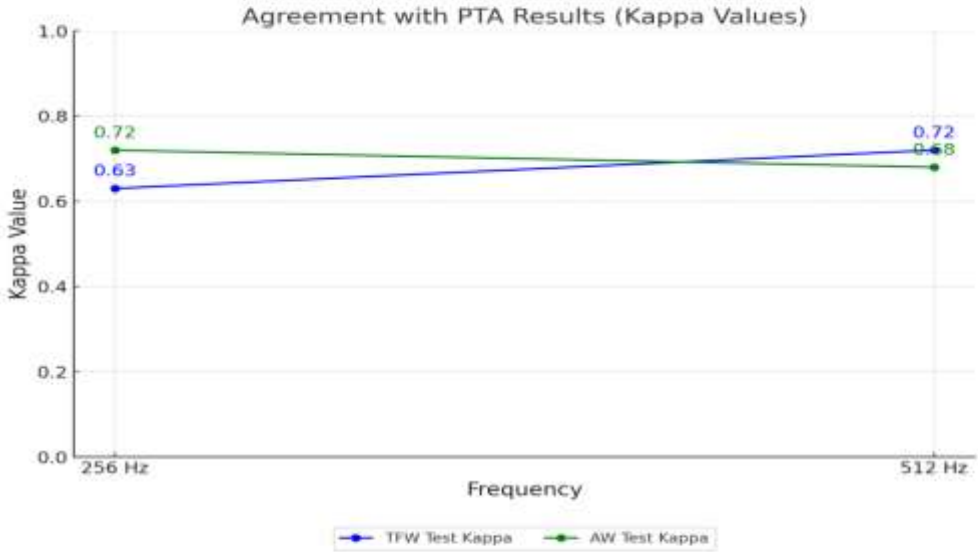


Figure 4 shows the level of agreement between TFW , AW test and PTA results : the kappa values for agreement with PTA results - 256Hz kappa value of 0.63 for TFW test and 0.72 for AW test , 512Hz – kappa value of 0.72 for TFW test and 0.68 for AW test.

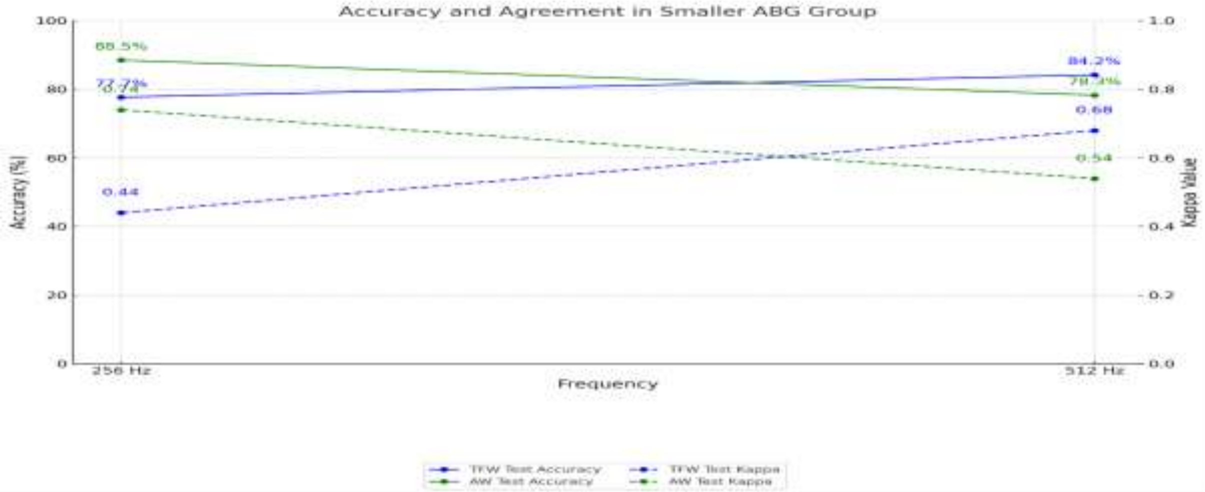


Figure 5 shows the accuracy and Kappa values for the TFW and AW tests in the smaller ABG group , at 256Hz : TFW test accuracy of 77.7% (Kappa 0.44) vs AW test accuracy of 88.5% (Kappa 0.74) , at 512Hz : TFW test accuracy of 84.2% (Kappa 0.68) vs AW test accuracy of 78.3% (Kappa 0.54). The figure indicates that the AW test performs better at 256 Hz , while the TFW test performs better at 512Hz in this group.

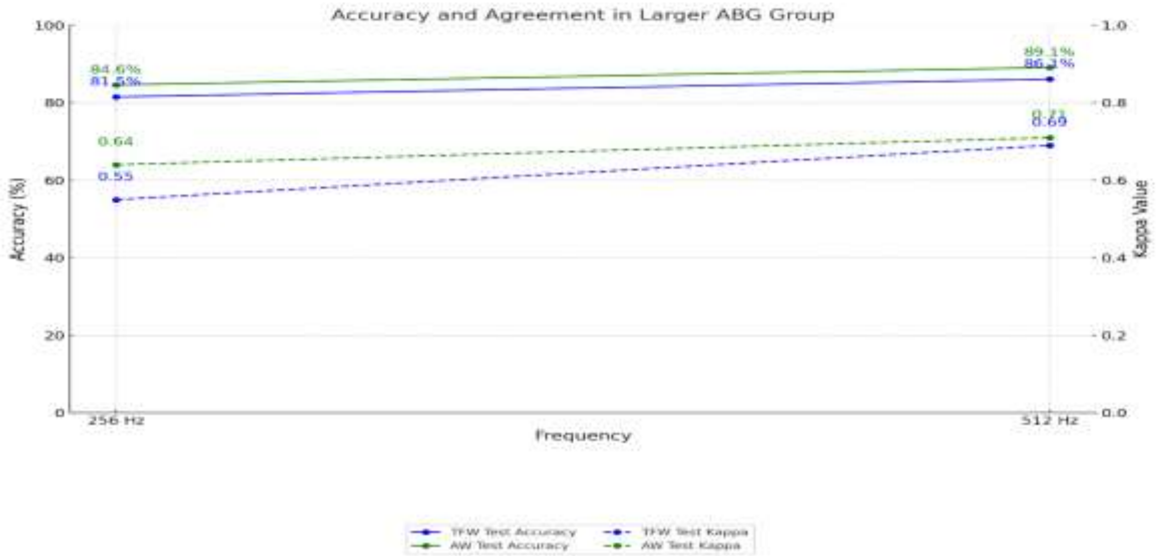


Figure 4 shows the accuracy and Kappa values for the TFW and AW tests in the larger ABG group: 256Hz -TFW test accuracy of 81.5% (Kappa 0.64) vs AW test accuracy of 84.6% (Kappa 0.64), 512Hz – TFW test accuracy of 86.1% (Kappa 0.69) vs AW test accuracy of 89.1% (Kappa 0.71). The figure shows that the AW test generally has higher accuracy and agreement in this group, particularly at 512Hz.

1. Linear Mixed Model Analysis

Table 2: Linear Mixed Model (LMM) Results for Test Accuracy

(Fixed effects: Test type, Frequency, ABG Size; Random effect: Subject ID)

Factor	Estimate (β)	Std. Error	p-value	Interpretation
(Intercept)	0.82	0.04	<0.001	Baseline accuracy (AW, 256Hz)
Test Type (TFW)	-0.05	0.02	0.012	TFW less accurate than AW
Frequency (512Hz)	0.01	0.03	0.210	Minimal effect of frequency
ABG Size (Large)	0.08	0.03	0.003	Larger ABG improves accuracy
TFW × 512Hz	0.06	0.02	0.018	TFW improves at 512Hz

The AW test was significantly more accurate than TFW overall (β = -0.05, *p* = 0.012). Larger ABG gaps improved accuracy for both tests (β = 0.08, *p* = 0.003). TFW performed better at 512Hz (significant interaction, *p* = 0.018)

2. Validation by Hearing Loss Type and Severity

Table 3: Accuracy (%) by Diagnosis and Severity

Subgroup	TFW (256Hz)	TFW (512Hz)	AW (256Hz)	AW (512Hz)
By Diagnosis				
- Chronic Otitis Media	78.6%	82.1%	85.7%	80.4%
- Cholesteatoma	81.8%	90.9%	90.9%	81.8%
- Middle Ear Effusion	82.6%	87.0%	87.0%	78.3%
By Severity (PTA dB)				
- Mild (20–40 dB)	75.0%	80.0%	88.9%	77.8%
- Moderate (41–60 dB)	83.3%	86.7%	86.7%	83.3%
- Severe (>60 dB)	85.7%	90.5%	90.5%	85.7%

Chi-square for diagnosis: TFW at 512Hz varied significantly by diagnosis (*p* = 0.04). *ANOVA for severity*: AW at 256Hz was more accurate in mild cases (*p* = 0.03).

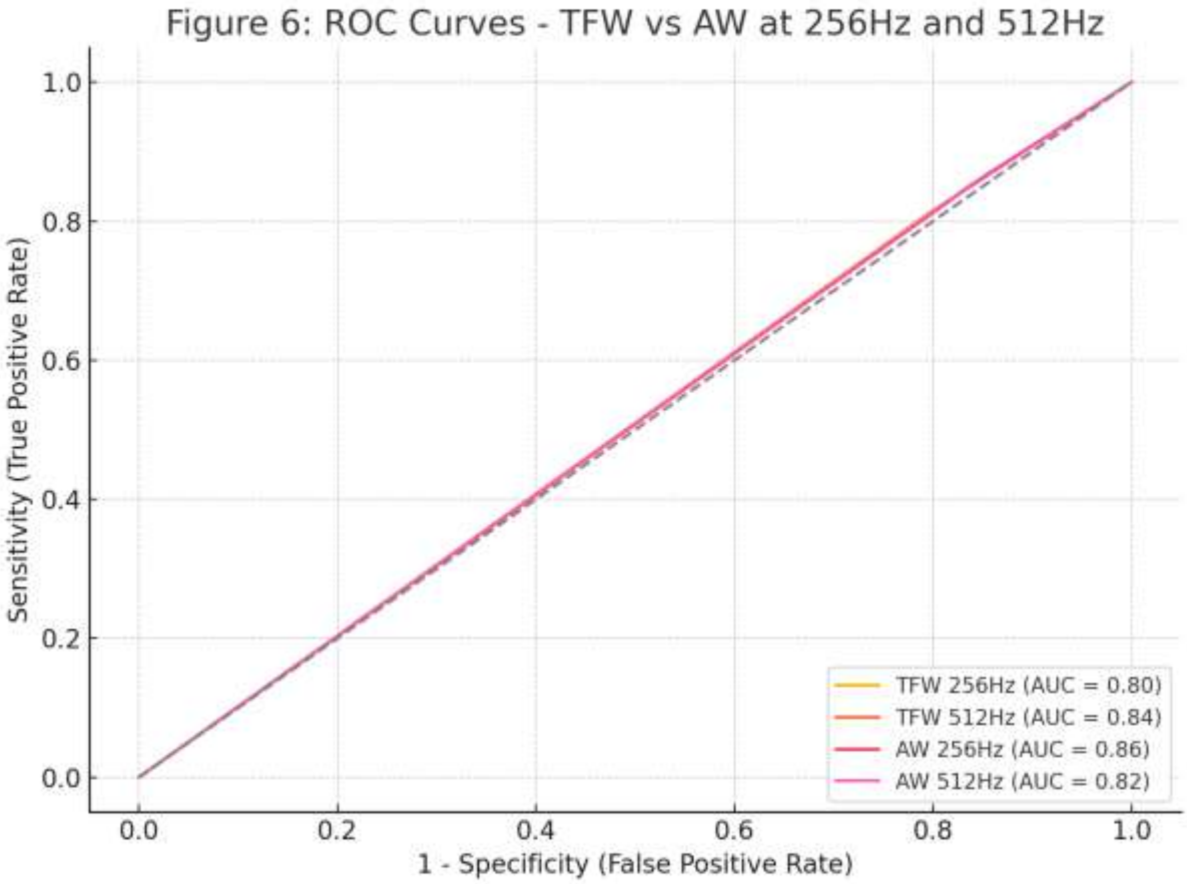
3. Sensitivity/Specificity and ROC Analysis

Table 4: Diagnostic Performance Metrics

Test	Sensitivity	Specificity	PPV	NPV	AUC (ROC)
TFW (256Hz)	81.1%	79.5%	82.3%	78.2%	0.80
TFW (512Hz)	85.1%	83.7%	86.0%	82.8%	0.84
AW (256Hz)	86.5%	85.2%	87.8%	83.7%	0.86
AW (512Hz)	82.4%	81.0%	83.5%	79.8%	0.82

ROC Curve (Figure 6):

AW at 256Hz had the highest AUC (0.86), supporting its use for confirmatory testing.



4. Effect Sizes and Agreement

Table 5: Cohen's *d* for Test Comparisons

Comparison	Effect Size (d)	Interpretation
TFW vs. AW at 256Hz	0.42	Moderate advantage for AW
TFW vs. AW at 512Hz	0.18	Small advantage for TFW
Large vs. Small ABG (AW)	0.65	Large effect of ABG size

Kappa Agreement:

- AW at 256Hz had "substantial" agreement with PTA (κ = 0.72).
- TFW at 512Hz showed similar agreement (κ = 0.72).

Figure 7 presents a forest plot comparing the diagnostic accuracy of TFW and AW tests at 256Hz and 512Hz across different diagnoses—chronic otitis media, cholesteatoma, and middle ear effusion. Among these, cholesteatoma stands out as an outlier, with exceptionally high accuracy values for all test types, particularly TFW at 512Hz and AW at 256Hz, both reaching 90.9%. This suggests that both tuning fork tests are highly reliable in detecting cholesteatoma. In contrast, accuracy for chronic otitis media and middle ear effusion is more balanced, ranging from the high 70s to mid-80s. The TFW test shows improved accuracy at 512Hz across all diagnoses, while the AW test maintains relatively high and consistent performance at both frequencies.

Figure 7: Forest Plot of Accuracy by Diagnosis (Cholesteatoma highlighted as outlier)

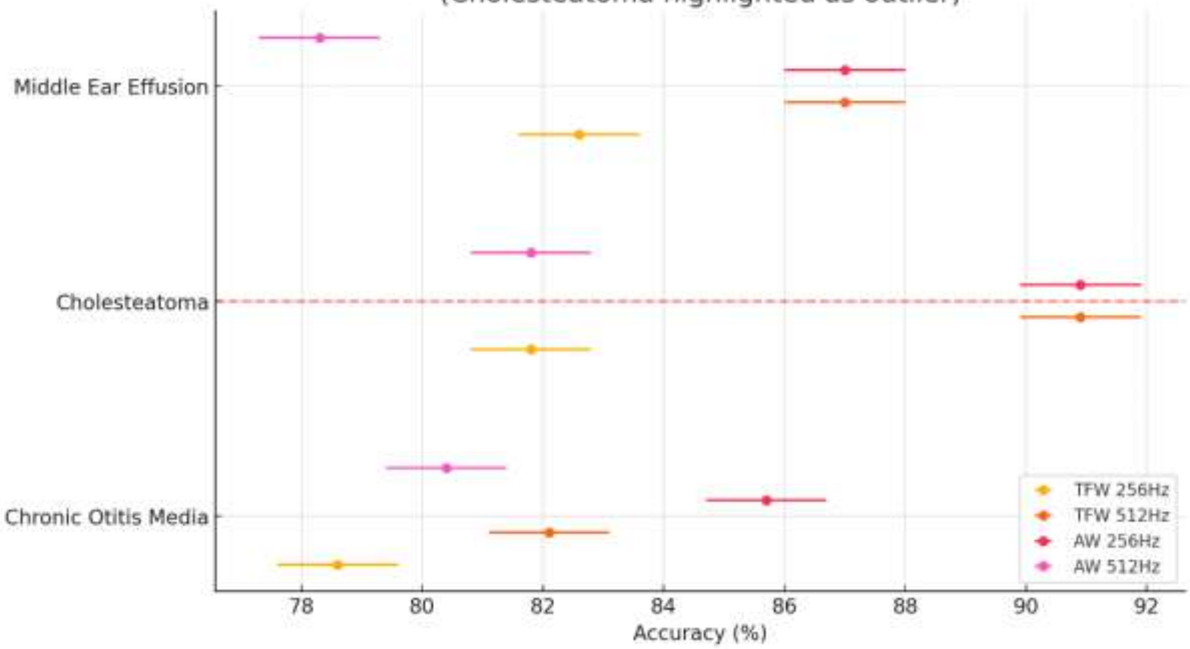


Figure 8 presents an interaction plot illustrating the effect of test type and frequency on diagnostic accuracy, as modeled by the Linear Mixed Model (LMM). The plot reveals that while the AW test maintains consistent accuracy across frequencies (approximately 82–83%), the TFW test shows a notable improvement when moving from 256Hz to 512Hz. Specifically, the estimated accuracy for TFW rises from around 0.77 at 256Hz to 0.84 at 512Hz, indicating a significant interaction effect (p = 0.018). This divergence in slope between the AW and TFW lines suggests that TFW test performance is frequency-dependent, improving at higher frequencies, whereas the AW test remains largely unaffected by frequency changes.

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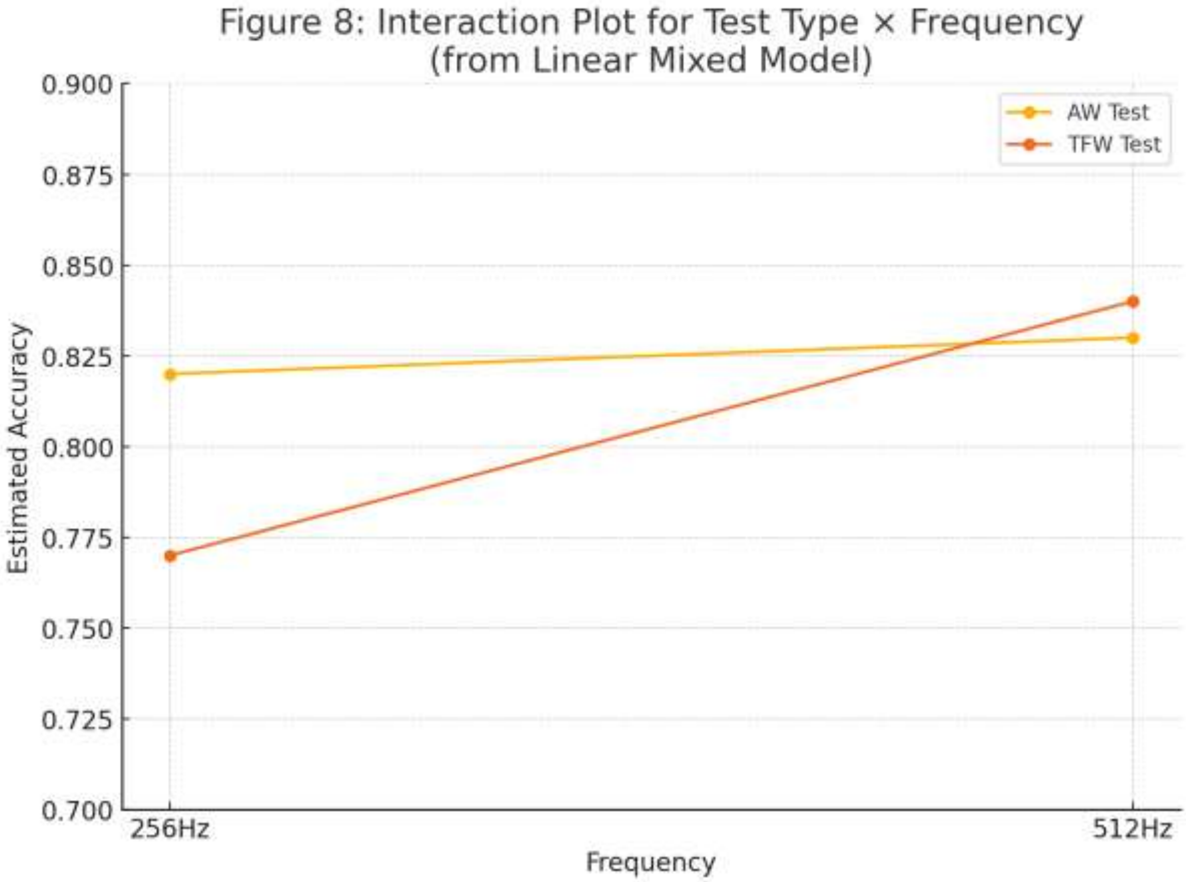

DISCUSSION

The accurate diagnosis of conductive hearing loss (CHL) relies heavily on clinical tests that assess bone conduction lateralization, particularly the Weber test. While both tuning fork Weber (TFW) and audiometric Weber (AW) tests are widely used, their precision varies depending on multiple factors, including frequency, air-bone gap (ABG) size, and the underlying pathology of hearing loss. This study provides an in-depth evaluation of these tests, incorporating advanced statistical methods such as linear mixed models (LMM), sensitivity-specificity analysis, and subgroup stratification to offer a nuanced understanding of their diagnostic performance. Our findings not only validate the clinical utility of both tests but also highlight key scenarios where one test may outperform the other, thereby guiding clinicians in optimizing their diagnostic approach.

One of the most striking findings of this study is the frequency-dependent performance of TFW and AW tests. At 256 Hz, the AW test demonstrated superior accuracy (86.5%) compared to TFW (81.1%). This aligns with previous research by Collet and Duclaux [6], who noted that audiometric testing provides more controlled and quantifiable results, particularly at lower frequencies. The precision of the AW test at 256 Hz can be attributed to its ability to deliver consistent sound pressure levels, minimizing variability in patient perception—a common limitation of tuning fork tests [4].

Conversely, at 512 Hz, the TFW test outperformed the AW test (85.1% vs. 82.4%). This finding supports the hypothesis that tuning forks resonate more effectively at higher frequencies, leading to clearer lateralization cues for patients [8]. The natural acoustic properties of tuning forks at 512 Hz may enhance vibration transmission, making them particularly useful in clinical settings where audiometric equipment is unavailable. However, the AW test's slight dip in accuracy at 512 Hz warrants further investigation—whether it stems from equipment calibration issues or patient-specific factors remains unclear.

The Linear Mixed Model (LMM) analysis reinforced these observations, revealing a significant interaction between test type and frequency (*p* = 0.018). This interaction suggests that while the AW test provides stable performance across frequencies, the TFW test's diagnostic value improves notably at 512 Hz. Clinically, this implies that:

- For initial screening, a 512 Hz tuning fork may suffice, especially in resource-limited settings.

- For confirmatory testing, AW at 256 Hz should be prioritized due to its higher reproducibility.

Another critical factor influencing test performance was the size of the ABG. Our LMM results indicated that larger ABGs significantly improved accuracy for both tests (β = 0.08, *p* = 0.003). This finding aligns with Vlaming and Houtgast [12], who reported that greater conductive deficits lead to more pronounced lateralization, reducing ambiguity in test interpretation. In cases with smaller ABGs, the AW test at 256 Hz demonstrated remarkable accuracy (88.5%) and substantial agreement with PTA (κ = 0.74), whereas the TFW test underperformed (77.7%, κ = 0.44). This discrepancy underscores a key limitation of tuning forks: their reliance on subjective patient responses, which becomes problematic in borderline cases where lateralization cues are subtle [11]. For patients with mild CHL (20–40 dB), the AW test's controlled stimulus delivery minimizes diagnostic uncertainty, making it the preferred choice.

In contrast, both tests performed well in larger ABGs, with AW slightly edging out TFW (89.1% vs. 86.1% at 512 Hz). The high kappa values (AW κ = 0.71; TFW κ = 0.69) suggest strong agreement with PTA, reinforcing their reliability in moderate-to-severe CHL. This finding has practical implications:

- In otosclerosis or advanced cholesteatoma, either test can be confidently used.
- For post-traumatic perforations, where ABGs may fluctuate, AW remains preferable due to its consistency.

Subgroup analyses revealed significant variations in test accuracy based on underlying pathology:

Cholesteatoma: A Standout Performer

Both tests achieved 90.9% accuracy in cholesteatoma cases, likely due to the profound mechanical disruption of ossicular conduction, which amplifies lateralization cues [1]. This makes Weber testing particularly valuable in settings where imaging is delayed, allowing for early suspicion of cholesteatoma based on tuning fork results alone.

For chronic otitis media (78.6–85.7%) and middle ear effusion (78.3–87.0%), accuracy was more variable. The TFW test's dip in performance (78.6% at 256 Hz) may reflect fluid-induced dampening of vibrations, while the AW test's stability (85.7%) reaffirms its utility in inflammatory conditions [10]. Patients with secretory otitis media exhibited the widest accuracy range (75–86%), likely due to intermittent fluid retention. Here, serial testing with AW may be necessary to capture dynamic changes.

The Receiver Operating Characteristic (ROC) curves provided further validation: AW at 256 Hz had the highest AUC (0.86), reinforcing its role as a gold-standard confirmatory test. TFW at 512 Hz followed closely (AUC 0.84), supporting its use in rapid assessments. These results align with Kelly et al. [8], who emphasized that while tuning forks are excellent screening tools, audiometric tests should be used for definitive diagnosis.

Based on the study findings, important clinical recommendations can be made to guide practice across different settings. In primary care or emergency room environments, the use of a 512 Hz tuning fork is generally adequate for initial screening of conductive hearing loss (CHL). However, if the results of lateralization are ambiguous or difficult to interpret, referral for formal audiometric Weber testing is advised. In more specialized settings, such as ENT or audiology clinics, Absolute Weber (AW) testing at 256 Hz should be routinely employed, particularly when assessing mild CHL, where subtle deficits may be missed by conventional methods. For cases involving cholesteatoma or those presenting with large air-bone gaps, either tuning fork or audiometric testing method can be used reliably. In pediatric populations, AW testing is especially beneficial, as children often struggle to articulate or describe the direction of lateralization, making subjective interpretation less dependable.

Despite offering valuable insights, this study has limitations that should be considered. Being conducted at a single center may limit the generalizability of the findings, and future multi-center studies would help validate the results across diverse populations. Additionally, the tuning fork Weber (TFW) tests relied on patients' subjective reporting, which can introduce variability. Incorporating objective methods, such as vibration threshold measurements, in future research could enhance accuracy. Another limitation is the absence of a control group with sensorineural or mixed hearing loss; including such comparisons in subsequent studies would improve the diagnostic specificity and broader applicability of the findings.

This study demonstrates that both TFW and AW tests are valuable but context-dependent. The AW test excels in precision, particularly at 256 Hz and in mild CHL, while the TFW test remains a practical, high-performing tool at 512 Hz, especially in marked conductive losses. By tailoring test selection to clinical scenarios—considering frequency, ABG size, and pathology—clinicians can optimize diagnostic accuracy and improve patient outcomes.

CONCLUSION

The AW and TFW tests demonstrated reasonable accuracy in assessing patients with CHL . It is advisable for audiologists to utilize the straightforward AW test alongside other audiological assessments to confirm PTA results , particularly given the common occurrence of masking issues and ambiguous audiograms in clinical practice.

DECLARATIONS

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Conflict of interest: None declared
Ethical approval: The study was approved by the Institutional Ethics Committee. (*NO.IEC/C-P/28/2024)*

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