An Investigation Into the Clinical Utility of Speech Reception Threshold, Bone Conduction, and Word Recognition Scores in the Standard Audiological Test Battery

Évaluation de l'utilité clinique du seuil de réception de la parole, de la conduction osseuse et des scores de reconnaissance de mots dans la batterie de tests utilisée en audiologie

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Abstract

The purpose of this study was to examine the functional utility of the speech reception threshold, bone conduction, and word recognition score measurements which are generally used in the audiological test battery. In this retrospective single-observation study, pure-tone audiometry and speech audiometry findings were compared with objective hearing assessments, that is, tympanometry, acoustic reflex threshold, and distortion product otoacoustic emissions. Data were retrieved from records of 134 patients; of these, 57.5% had sensorineural hearing loss, and 12.3%, 24.6%, and 5.6% had normal hearing, mixed hearing loss, and conductive hearing loss, respectively. The results showed that the values of distortion product otoacoustic emissions were abnormal among a significant number of people diagnosed with normal hearing according to pure-tone audiometry. The correlations between the degree of hearing loss and the speech reception threshold and the word recognition score were moderate and low, respectively. Furthermore, an air-bone gap greater than 10 dB was present in approximately 25% of patients with findings of normal tympanogram, acoustic reflex threshold, and distortion product otoacoustic emissions. In several cases, the use of bone conduction, speech reception threshold, and word recognition score added only a limited diagnostic value. In conclusion, this study suggests that rather than having a fixed number of tests in the test battery, case-based inclusion of tests that add specific value to diagnosis can simplify the standard audiological test battery, leading to overall enhancements in the hearing assessment process.

Abrégé

L’objectif de la présente étude était d’examiner l’utilité fonctionnelle de mesures généralement incluses dans la batterie de tests utilisée en audiologie, soit le seuil de réception de la parole, la conduction osseuse et les scores de reconnaissance de mots. Dans cette étude observationnelle rétrospective monocentrique, les résultats d’audiométries tonales et vocales ont été comparés aux résultats de mesures objectives de l’audition, soit la tympanométrie, la mesure des réflexes stapédiens et les émissions otoacoustiques par produit de distorsion. Les données provenant des dossiers de 134 patients ont été récupérées. Parmi ces 134 patients, 57,5 % avaient une perte auditive neurosensorielle, 12,3 % avaient une audition normale, 24,6 % avaient une perte auditive mixte et 5,6 % avaient une perte auditive conductive. Les résultats ont montré que les valeurs des émissions otoacoustiques par produit de distorsion étaient anormales pour un nombre important de personnes ayant une audition normale selon les résultats de l’audiométrie tonale. Les corrélations entre le degré de l’atteinte auditive et le seuil de réception de la parole et les scores de reconnaissance de mots étaient modérées et faibles, respectivement. De plus, un écart aérien-osseux supérieur à 10 dB a été constaté pour environ 25 % des patients chez qui le tympanogramme, le seuil de déclenchement du réflexe stapédien et les émissions otoacoustiques par produit de distorsion étaient normaux. Pour de nombreux individus, l’évaluation par conduction osseuse et l’utilisation du seuil de réception de la parole et du score de reconnaissance de mots ont contribué de façon limitée au diagnostic. En conclusion, cette étude suggère qu’il est possible de simplifier la batterie de tests utilisée en audiologie en incluant au cas par cas les tests qui contribuent concrètement à la pose d’un diagnostic, au lieu d’utiliser le nombre prédéterminé de tests inclus dans la batterie. Cela conduit à une amélioration générale du processus d’évaluation de l’audition.

According to the World Health Organization, by 2050, more than two billion people are projected to have some degree of hearing loss, and at least 700 million people will have disabling hearing loss (World Health Organization, 2021). The impact of hearing loss on quality of life is significant and multifaceted; however, the degree of difficulties associated with hearing loss and its impact on quality of life is subjective (Gatehouse & Noble, 2004). Therefore, an early and accurate hearing assessment can substantially help in the effective and timely clinical management and rehabilitation of patients.

A number of assessment tools exist to evaluate the extent of hearing loss; however, there is a lack of consensus among researchers on the adequacy of these tests. Hearing assessment generally involves an audiological test battery consisting of otoscopy, pure-tone audiometry, speech reception thresholds (SRT) obtained in quiet, and word recognition scores (WRS) obtained in quiet (Emanuel et al., 2011; Taylor, 2004). Because this test battery is generally used in all cases regardless of the diagnostic efficacies of the individual tests in the battery, there is concern that such indiscriminate use could burden patients with unnecessary medical costs and procedure time.

Pure-tone audiometry is the most common auditory technique used to determine air conduction (AC) and bone conduction (BC) thresholds (Convery et al., 2014). In pure-tone testing, frequencies covering almost the entire speech spectrum (250–8000 Hz for AC and 250–4000 Hz for BC) are used to determine if the patient's hearing threshold falls within normal limits. AC thresholds are the softest audible acoustic signals that travel through the external, middle, and inner ears using headphones or earphones, and BC thresholds are the audible acoustic signals that vibrate the skull to stimulate the inner ear (cochlea) using a bone vibrator. The air-bone gap (ABG), which is defined as the difference between AC and BC thresholds, is frequently used to determine the type of hearing loss (conductive, sensorineural, or mixed; Margolis & Saly, 2008; Tanna et al., 2021). In conductive hearing loss, AC is abnormal, but BC is normal or near normal (from −10 to 15 dB hearing level [HL]), and the ABG is greater than 10 dB HL. If the AC and BC thresholds fall in the abnormal range, but the ABG is less than or equal to 10 dB HL, the loss is defined as sensorineural hearing loss. A mixed-type hearing loss has components of both conductive and sensorineural origin, that is, if both AC and BC are abnormal and the ABG is greater than 10 dB (Scarpa et al., 2020), the loss is defined as a mixed hearing loss. Although many clinicians rely on the audiogram for the diagnosis of hearing loss, a false ABG can result in inappropriate diagnosis and case management (Margolis, 2010; Studebaker, 1967). Therefore, additional tests are generally included to reach a more definitive diagnosis of hearing loss and provide appropriate recommendations for clinical management (**Table 1**; Gelfand, 2016; Hall, 2017; Schlauch et al., 2014).

In hearing assessment, speech audiometry tests, SRT, and WRS complement pure-tone audiometry and provide critical information about an individual's ability to understand speech. SRT represents the lowest sound level at which 50% of the stimuli used in the test are clearly recognized by an individual (Gelfand, 2016). It has a significant association with pure-tone average (PTA; Toledo dos Anjos et al., 2014), and the variances between SRT and PTA are usually less than 10 dB (Gelfand, 2016). SRT may add value in hearing-aid fitting (Van Tasell & Yanz, 1987). SRT provides an index of the hearing sensitivity of speech and assists in ascertaining the starting position for other suprathreshold tests such as WRS. The WRS is also termed a speech discrimination score. It is a measure of the percentage of words repeated correctly, providing information about the phonemes and the respective intensity level that the patients do not correctly identify (Billings et al., 2016). It is obtained at a suprathreshold level, with the patient repeating phonetically balanced single-syllable words presented in quiet, usually in lists of 25 words. The purpose of WRS is to provide information about word discrimination abilities and to estimate communication difficulties (McRackan et al., 2016). Typically, WRS is performed with the intent of obtaining information about speech neural processing, as retrocochlear pathologies exhibit abnormally low WRS.

In most audiology clinics, AC, BC, and SRT in quiet are performed with almost all patients, and WRS in quiet is evaluated at only one presentation level. Objective tests such as tympanometry, acoustic reflex threshold (ART), and otoacoustic emission (OAE) measurements offer direct and sensitive measurement of middle ear function (Jerger, 1970). A survey examining the diagnosis and intervention protocols used by audiologists revealed that audiologists perform four hearing tests with most patients: pure-tone audiometry in 100%, tympanometry in 97%, SRT in 92%, and WRS in quiet in 90% (Emanuel et al., 2011). The same study also pointed out that other speech and objective auditory tests such as ART, OAE, WRS, acoustic reflex decay, and phonetically balanced functions tests are performed less frequently. Recently, Windmill and Freeman (2019) reported data on audiological procedures performed in the hearing assessment of older adult patients in the United States. Data were derived from the current procedural terminology code used for health insurance payments. The study found

Table 1

Clinical Conditions Where BC, SRT, and WRS May or May Not Add Value in the Diagnosis and Management of Hearing Loss

Test	Adds value with	Does not add value with	Other tests that add more value
BC	History of middle ear disorders	Normal hearing sensitivity Normal otoscopy Normal findings on tympanometry and OAE Sloping hearing loss	Tympanometry OAE
SRT	Flat hearing loss Nonorganic hearing loss Age ≤ 18 Age ≥ 65 Difficult to test populations	Normal hearing sensitivity Sloping hearing loss Patients between 19 and 64 years	Auditory brainstem response Acoustic reflex tone decay Words-in-noise tests Sentences-in-noise tests Dichotic listening tests Pure-tone Stenger for nonorganic hearing loss Performance intensity phonetically balanced function test
WRS	Suspected retrocochlear pathology Noise-induced hearing loss Hyperacusis Asymmetric hearing loss	Normal hearing sensitivity	

Note. With information from Gelfand (2016) and Schlauch et al. (2014). BC = bone conduction; SRT = speech reception threshold; WRS = word recognition scores; OAE = otoacoustic emission.

that AC, BC, SRT, and WRS were performed for 90% of audiology referrals; tympanometry alone was performed for 81%, tympanometry and ART were performed for 18.5%, and OAEs were performed for 11.5% of audiology referrals. These studies reflect that in most audiology clinics, AC, BC, and SRT in quiet are performed indiscriminately, without much consideration of the diagnostic value added by a specific test to a particular case.

Given the diversity of auditory dysfunctions, it is not likely that all tests included in the traditional test battery will contribute equally or even substantially to the diagnosis of hearing loss. However, no reports have been published that examine the clinical utility of BC, SRT, and WRS in audiological evaluation. The current study aims to address this issue by performing a comprehensive evaluation of the clinical utility of BC, SRT, and WRS in assessing the type and severity of hearing loss. This study also compares the results of these tests with the findings of objective tests such as tympanometry, ART, and OAE. Finally, based on the results, recommendations for the case-specific selection of audiological tests are presented.

Methods

This single-observation retrospective study was approved by the Institutional Review Board at Bloomsburg University of Pennsylvania (#2018-59). Demographic data, case history, and hearing test results were retrieved from files of 134 patients (71 men and 63 women) who underwent an initial audiological evaluation between 2010 and 2018 at the Bloomsburg University Speech-Language and Hearing Clinic. The median age was 63.5 years, with an age range of 8 to 89 years, and only 9 (6.7%) patients were less than 18 years old. Records of patients tested with AC, BC, SRT, WRS, tympanometry, ART, and OAEs were included.

Outcome Variables

The data extracted from the files were age, sex, year, type of test, test procedure, and the instrument used. The key outcome variables included normal and abnormal findings in AC, BC, SRT, WRS, tympanometry, ART, and OAEs among patients with different types of hearing loss. The following sections provide additional methodological information and definitions of the data retrieved in this study.

Test Procedures and Definitions

The tests were performed with clinical audiometers (Grason-Stadler 61, Grason-Stadler Audiostar Pro, Madsen Astera). The equipment was calibrated annually by a certified technician using the American National Standards Institute S3.6-1996 and S3.39-1987 standards (American

National Standards Institute, 1987, 1996). The transducers used were E-A-R tone 3A insert earphones, Telephonics TDH-50P/TDH-39P headphones, and a B-71 bone vibrator. AC thresholds were measured at frequencies of 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. BC thresholds were measured at frequencies of 500, 1000, 2000, and 4000 Hz. Thresholds were estimated using the American Speech-Language-Hearing Association procedure using +5 dB after an incorrect response and −10 dB steps after a correct response (American Speech-Language-Hearing Association, 2005). Thresholds at frequencies of 750 and 1500 Hz were measured in cases where the interoctave threshold difference was greater than 20 dB HL.

Normal hearing sensitivity was defined as thresholds of 25 dB HL or lower at pure-tone frequencies from 250 to 8000 Hz (Moncrieff et al., 2013; Rosen et al., 2010). *Asymmetric hearing loss* was defined as a threshold difference of 15 dB or more at two or more frequencies between 250 and 8000 Hz (Cueva, 2004). The configuration of hearing loss was determined using average interoctave differences (Katz, 1978; Katz et al., 2014) with the following criteria: *sloping* is 5 dB or more; *rising* is −5 dB or less; and *flat/other* is between −5 and +5 dB. The type of hearing loss was determined from the findings of pure-tone audiometry and classified using criteria reported by Gelfand (2001, 2016) and Kramer and Brown (2018). *Sensorineural hearing loss* was defined by abnormal AC and BC with ABG of 10 dB HL or less. *Conductive hearing loss* was defined by abnormal AC and normal BC with an ABG of more than 10 dB HL at at least one frequency. *Mixed hearing loss* was defined by abnormal AC and BC with an ABG of more than 10 dB HL at at least one frequency.

SRT was measured monaurally in quiet using recorded spondee words and was determined via the modified American Speech-Language-Hearing Association (1988) ballpark estimate procedure. The recorded spondee words were delivered from lists available on the Grason-Stadler Inc. (GSI) Audiostar Pro and Madsen Astera. Participants were evaluated with the GSI 61 audiometer. Spondees materials (Harris, 1991) were delivered via a Denon compact disc/MP3 player routed through the speech channels of the audiometer.

WRS in quiet was measured using recorded phonetically balanced word lists at one intensity level for the majority of patients using Central Institute for the Deaf W-22 materials (Hirsh et al., 1952). The level of presentation of the WRS was selected based on the recommendations of Guthrie and Mackersie (2009), specifically with reference to the pure-tone AC threshold for 2000 Hz: using 25 dB sensation level (SL) if the threshold is less than 50 dB HL, 20 dB SL if the threshold is 50 to 55 dB HL; 15 dB SL if the threshold is 60 to 65 dB HL, 10 dB SL if the threshold is 70 to 75 dB HL, or presenting the words at 5 dB below the uncomfortable level.

Tympanometry was performed with a 226 Hz probe tone with either a GSI 33, GSI Tympstar, or a GSI Tympstar Pro aural immittance device. Pressure change was set from +200 to −400 daPa with a sweep rate of 600/200 daPa/s. Tympanometry was classified as normal based on the following criteria: static admittance between 0.27 and 1.7 mmho, peak pressure +100 to −150 daPa, and ear canal volume 0.9 to 2.0 ml for adult participants and 0.3 to 0.9 ml for participants under the age of 10 years (Gelfand, 2001; Martin & Clark, 2018; Oeding et al., 2016; Roeser, 2013). Using a 226 Hz probe tone, ipsilateral ARTs were measured with a visual inspection for pure-tone stimuli of 500, 1000, and 2000 Hz. A criterion of repeatable admittance changes of 0.02 mmho or greater was used to determine the ART (Katz, 1978). If the ART was abnormally elevated (≥ 105 dB HL) or absent for at least one frequency, it was classified as abnormal according to normative data reported by Gelfand et al. (1990).

Distortion product otoacoustic emissions (DPOAEs) were measured for f2 frequencies of 842, 1001, 1184, 1416, 1685, 2002, 2380, 2832, 3369, 4004, 4761, 5652, 6726, 7996 Hz using the Otodynamics–ILO V6. The test protocol included L1 = 65 dB and L2 = 55 dB, and f2/f1 ratio = 1.22. Distortion product (DP)-gram was measured only once with multiple sweeps across frequencies. DPOAE findings were classified into three groups based on the normative (Dhar, 2011; Gorga et al., 2002; Hall, 2017). *Present and normal* was defined as a 6 dB difference between the DP amplitude and noise floor at approximately 70% of the collected data points, absolute DP amplitude within the normal range for the patient's age range, and a noise floor less than −10 dB SPL. *Present but not normal* was defined by more than 6 dB difference between the DP amplitude and noise floor, the absolute DP amplitude below normal limits for the patient's age, or the present DPOAE at less than 70% of the collected data points. *Absent* DPOAEs were defined as DPOAE amplitude less than 6 dB above the noise floor at all frequencies.

PTAs ($PTA_{0.5-2}$ and $PTA_{0.5-4}$) are good predictors of speech reception and recognition, respectively (Toledo dos Anjos et al., 2014). $PTA_{0.5-2}$ was the mean of thresholds for test frequencies of 500, 1000, and 2000 Hz, whereas $PTA_{0.5-4}$ was the mean of thresholds for frequencies of 500, 1000, 2000, 3000, and 4000 Hz. The degree of hearing loss was median SRT, the WRS values were further compared with the different types, and the degree of hearing loss was defined in different severity levels depending on the PTA values. Hearing loss was considered *normal, slight, mild, moderate, moderately severe, severe,* and *profound* for hearing thresholds of less than15 dB HL, 16–25 dB HL, 26–40 dB HL, 41–55 dB HL, 56–70 dB HL, 71–90 dB HL and greater than 91 dB HL respectively.

Statistical Analysis

Data were analyzed using descriptive statistics and frequency analysis with IBM SPSS Statistics for Windows (Version 26.0). Abnormal findings were compared among diagnostic test procedures, including tympanograms, ART, DPOAEs, SRT, WRS, and ABG. Furthermore, the findings of diagnostic tests were compared between the ears of participants with and without a history of hearing loss. The utility of SRT and WRS was evaluated by determining the relationship between pure-tone audiometry, SRT, WRS, and age. Kolmogorov-Smirnov and Shapiro-Wilk tests were performed to check for normality of the distribution of scores.

Results

Hearing Loss Type

The PTA findings revealed that most of the participants had sensorineural hearing loss (*n* = 154, 57.5%, **Table 2**). Almost 25% of the participants had mixed hearing loss, and conductive hearing loss was diagnosed in only 5.6% of the participants. About 12% of the participants had normal hearing. Based on PTA$_{0.5\text{-}4}$ levels, the degree of hearing loss was severe or worse in only 3.3% of the participants. Evaluation on the basis of PTA$_{0.5\text{-}2}$ yielded a slightly different degree of hearing loss (**Table 3**).

Objective and Behavioural Tests

Table 4 presents the findings of objective and behavioural tests for participants identified with different types of hearing loss. Among 33 cases diagnosed with normal hearing based on pure-tone audiometry data, almost 50% had abnormal or present but abnormal DPOAE. Similarly, 40% of patients with conductive hearing loss were classified as normal on the basis of DPOAE. However, for patients with mixed or sensorineural hearing loss, only one participant had normal DPOAE, although present but abnormal was observed for an appreciable number of participants. In the majority of patients with normal hearing (97%), the tympanograms were normal; however, they were also normal in more than 80% of cases of conductive, mixed, or sensorineural hearing loss. In the ART examination, more than 70% of the participants with conductive, mixed, or sensorineural hearing loss were diagnosed as normal. Interestingly, none of the participants with conductive hearing loss were found to be abnormal in SRT, and for mixed or sensorineural hearing loss, more than 40% of the participants were also identified as normal. Furthermore, a greater number of

Table 2

Distribution of Type and Degree of Hearing Loss Based on Pure-Tone Audiometry

Parameter	*n* (%)
Type of hearing loss	
NH	33 (12.3%)
SNHL	154 (57.5%)
MHL	66 (24.6%)
CHL	15 (5.6%)
Degree of hearing loss in dB HL [a]	
Normal (−10 to 15)	34 (12.7%)
Slight (16 to 25)	53 (19.8%)
Mild (26 to 40)	84 (31.3%)
Moderate (41 to 55)	66 (24.6%)
Moderately severe (56 to 70)	22 (8.2%)
Severe (71 to 90)	7 (2.6%)
Profound (91+)	2 (0.7%)

Note. NH = normal hearing; SNHL = sensorineural hearing loss; MHL = mixed hearing loss; CHL = conductive hearing loss; HL = hearing level.
[a] Based on PTA$_{0.5\text{-}4}$ = pure-tone average at 500, 1000, 2000, 3000, and 4000 Hz.

Table 3

Degree of Hearing Loss Based on $PTA_{0.5\text{-}2}$

Degree of hearing loss in dB HL	*n* (%)
Normal (−10 to 15)	54 (20.1%)
Slight (16 to 25)	60 (22.4%)
Mild (26 to 40)	85 (31.7%)
Moderate (41 to 55)	49 (18.3%)
Moderately severe (56 to 70)	11 (4.1%)
Severe (71 to 90)	8 (3.0%)
Profound (91+)	1 (0.4%)

Note. $PTA_{0.5\text{-}2}$ = pure-tone average at 500, 1000, and 2000 Hz; HL = hearing level.

Table 4

Distribution of Normal (N) and Abnormal (A) Findings Among Different Type of Hearing Loss Based on Pure-Tone Audiometry

Parameter	Normal hearing (*n* = 33)	SNHL (*n* = 154)	MHL (*n* = 66)	CHL (*n* = 15)	Total (*N* = 268)	*p*
Age						< .001
Median age in years	32.0	67.0	65.5	25.0	63.5	
(Q1, Q3)	(15.0, 55.0)	(59.0, 75.0)	(52.0, 73.0)	(10.0, 42.0)	(51.0, 72.0)	
Tympanogram						.176
N	32 (97.0%)	130 (84.4%)	53 (80.3%)	13 (86.7%)	228 (85.1%)	
A	1 (3.0%)	24 (15.6%)	13 (19.7%)	2 (13.3%)	40 (14.9%)	
ART						.719
N	27 (81.8%)	113 (73.4%)	47 (71.2%)	11 (73.3%)	198 (73.9%)	
A	6 (18.2%)	41 (26.6%)	19 (28.8%)	4 (26.7%)	70 (26.1%)	
DPOAE [a]						< .001
N	17 (51.5%)	1 (0.6%)	0 (0.0%)	6 (40.0%)	24 (9.0%)	
Ab	12 (36.4%)	127 (82.5%)	54 (81.8%)	7 (46.7%)	200 (74.6%)	
P/A	4 (12.1%)	26 (16.9%)	12 (18.2%)	2 (13.3%)	44 (16.4%)	
SRT						< .001
N	32 (97.0%)	69 (44.8%)	28 (42.4%)	15 (100.0%)	144 (53.7%)	
A	1 (3.0%)	85 (55.2%)	38 (57.6%)	0 (0.0%)	124 (46.3%)	
SRT- $PTA_{0.5\text{-}2}$						.341
N	31 (93.9%)	134 (87.0%)	59 (89.4%)	15 (100.0%)	239 (89.2%)	
A	2 (6.1%)	20 (13.0%)	7 (10.6%)	0 (0.0%)	29 (10.8%)	
SRT- $PTA_{0.5\text{-}4}$						.007
N	31 (93.9%)	110 (71.4%)	44 (66.7%)	14 (93.3%)	199 (74.3%)	
A	2 (6.1%)	44 (28.6%)	22 (33.3%)	1 (6.7%)	69 (25.7%)	

Note. Continuous variables are presented as median (Q1, Q3), and categorical variables as number (*n*) and percentage (%). Categorical variables were examined by chi-square test and continuous variables by the Kruskal-Wallis test. ART = acoustic reflex threshold; DPOAEs = distortion product otoacoustic emissions; SRT = speech reception threshold; $PTA_{0.5\text{-}2}$ = pure-tone average at 500, 1000, and 2000 Hz; $PTA_{0.5\text{-}4}$ = pure-tone average at 500, 1000, 2000, 3000, and 4000 Hz; SNHL = sensorineural hearing loss; MHL = mixed hearing loss; CHL = conductive hearing loss.

[a] DPOAE findings were classified as normal (N), present but abnormal (P/A), or absent (Ab).

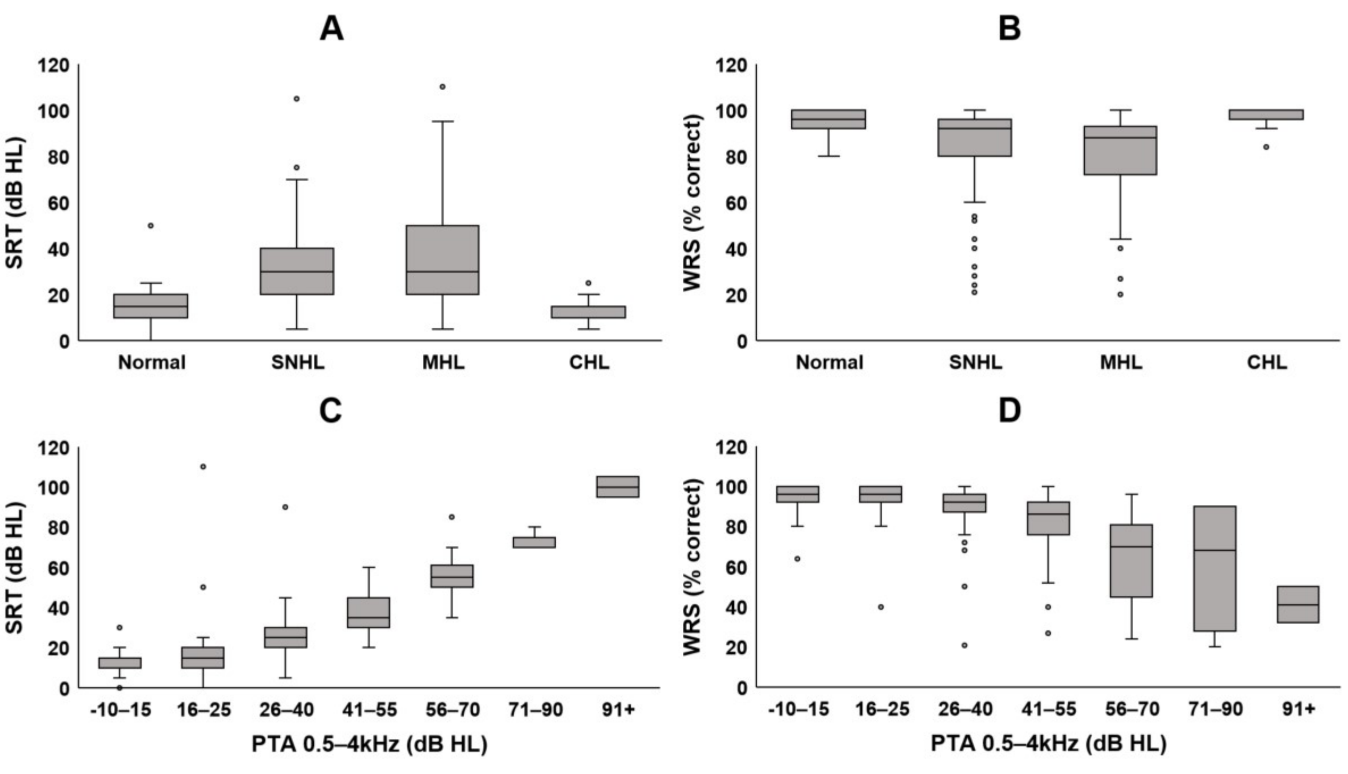
patients showed abnormal values of PTA$_{0.5\text{-}4\text{-SRT}}$ compared to PTA$_{0.5\text{-}2\text{-SRT}}$. With respect to the discriminating ability of SRT and WRS, differences in their median values were analyzed in different types of hearing loss.

Figure 1A–B depicts the median values of SRT and WRS in individuals with different types of hearing loss. It is obvious that the values in the mixed and sensorineural hearing loss groups are significantly different from the values in the normal hearing group. With an increase in the degree of hearing loss, there was a systematic increase in the SRT values and a decrease in the WRS values (**Figure 1C–D**). In patients with normal hearing or conductive hearing loss, the median SRT was l5 dB HL, and for those with mixed or sensorineural hearing loss, the median value was 30 dB HL. The WRS values were more than 90% up to 40 dB of PTA$_{0.5\text{-}4}$ (**Figure 1D**).

To determine the value added by SRT and WRS in predicting the degree and type of hearing loss, an ordinal logistic regression was performed. SRT predicted the degree of hearing loss using PTA$_{0.5\text{-}2}$ with McFadden $R^2 = .64$, $p < .01$, and PTA$_{0.5\text{-}4}$, $R^2 = .58$, $p < .01$. On the other hand, WRS was a poor predictor of the degree of hearing loss using PTA$_{0.5\text{-}2}$, $R^2 = .18$, $p < .01$ and PTA$_{0.5\text{-}4}$, $R^2 = .20$, $p < .01$. Neither SRT or WRS predicted the type of hearing loss.

A total of 25 patients (measurements in 50 ears) reported a history of disorders of the outer or middle ear, including otologic surgery, otalgia, otorrhea, otitis media, or aural fullness. Of these, the findings of DPOAE were abnormal in 70% and present but abnormal in 10% (**Table 5**). However, among patients without a history of ear disorders, the DPOAE findings were abnormal in 75.7% and present but abnormal in 17.9% of cases due to some degree of hearing loss. Furthermore, in patients with a history of hearing disorders, abnormal findings on tympanometry, ART, and SRT were 22%, 46.0%, and 42%, respectively. And in participants with no history of ear disorders (109 patients, 218 ears in which measurements were conducted), abnormal findings in tympanometry, ART, and SRT were 13.3%, 21.6%, and 47.2 %, respectively.

Figure 1



Type of hearing loss and SRT (A) and WRS (B); degree of hearing loss based on the magnitude of PTA$_{0.5\text{-}4}$ and SRT (C) and WRS (D)

Note. SNHL = sensorineural hearing loss; MHL = mixed hearing loss; CHL = conductive hearing loss; SRT = speech reception threshold; WRS = word recognition score; HL = hearing level; PTA$_{0.5\text{-}4}$ = pure-tone average of 500, 1000, 2000, 3000, and 4000 Hz in dB HL.

Table 5

Percentage of Ears With Normal (N) and Abnormal (A) Findings on Tympanometry, ART, DPOAE, and SRT for Participants With History of Ear Disorders

Parameter	No History of Ear Disorders ($n = 218$)	History of Ear Disorders ($n = 50$)	Total ($N = 268$)	p
Tympanogram				.120
N	189 (86.7%)	39 (78.0%)	228 (85.1%)	
A	29 (13.3%)	11 (22.0%)	40 (14.9%)	
ART				< .001
N	171 (78.4%)	27 (54.0%)	198 (73.9%)	
A	47 (21.6%)	23 (46.0%)	70 (26.1%)	
DPOAE[a]				.006
N	14 (6.4%)	10 (20.0%)	24 (9.0%)	
Ab	165 (75.7%)	35 (70.0%)	200 (74.6%)	
P/A	39 (17.9%)	5 (10.0%)	44 (16.4%)	
SRT				.502
N	115 (52.8%)	29 (58.0%)	144 (53.7%)	
A	103 (47.2%)	21 (42.0%)	124 (46.3%)	
SRT- $PTA_{0.5\text{-}2}$				.766
N	195 (89.4%)	44 (88.0%)	239 (89.2%)	
A	23 (10.6%)	6 (12.0%)	29 (10.8%)	
SRT- $PTA_{0.5\text{-}4}$				.964
N	162 (74.3%)	37 (74.0%)	199 (74.3%)	
A	56 (25.7%)	13 (26.0%)	69 (25.7%)	

Note. Categorical variables are presented as number (*n*) and percentage (%). Categorical variables were examined by chi-square test. ART = acoustic reflex threshold; DPOAEs = distortion product otoacoustic emissions; SRT: speech reception threshold; $PTA_{0.5\text{-}2}$ = pure-tone average at 500, 1000, and 2000 Hz; $PTA_{0.5\text{-}4}$ = pure-tone average at 500, 1000, 2000, 3000, and 4000 Hz.
[a] DPOAE findings were classified as normal (N), present but abnormal (P/A), or absent (Ab).

The results of objective tests, that is, tympanogram, ART, and DPOAE, were compared with the results of ABG, SRT, and WRS (**Table 6**). Among the patients with normal hearing, more than 40% were found to be abnormal on the SRT and WRS examinations, and 26.8% were abnormal according to the ABG test. Regarding abnormal tympanometry findings, ABG was normal in more than 60% of the cases. SRT and WRS were normal in 30% and 45% of the patients. In the case of ART, 70% of the normal findings were also normal in ABG, and close to 55% were normal in SRT and WRS. A substantial proportion of abnormal cases, as per DPOAE findings, were found to be abnormal in ABG, SRT, and WRS. In particular, 24 individuals were found to be normal according to the combined findings of tympanometry, ART, and DPOAE; however, in the SRT analysis, none of these were abnormal, and even in ABG and WRS, only 25% and 16.7% of the cases were abnormal.

Correlations Between Different Tests

Spearman correlation was performed to investigate the relationship between $PTA_{0.5\text{-}2}$, $PTA_{0.5\text{-}4}$, SRT, and WRS (**Table 7**); significance level alpha was set at .01. **Figure 2** represents the correlations between $PTA_{0.5\text{-}4}$ and SRT for different types of hearing loss. A positive correlation between $PTA_{0.5\text{-}4}$ and SRT was evident in all types of hearing loss. In the case of WRS and $PTA_{0.5\text{-}4}$, there was no correlation in the normal hearing group, but a negative correlation was clear in sensorineural and mixed hearing loss groups (**Figure 3**). $PTA_{0.5\text{-}2}$ was a better predictor and showed a stronger relationship with SRT ($r_s(268) = .90, p < .01$), whereas $PTA_{0.5\text{-}4}$ showed a moderate relationship with WRS ($r^s(268) = -.55, p < .01$). With age, SRT was positively related ($r^s(268) = .56, p < .01$) and WRS was negatively related ($r^s(268) = -.33, p < .01$). The relationship between SRT and PTA (SRT-PTA) was

Table 6

Comparison of Normal (N) and Abnormal (A) Findings on Tympanometry, ART, and DPOAEs for Participants with Abnormal ABG, SRT, and WRS.

Diagnostic tests (Number of ears)	ABG		SRT		WRS	
	N	A	N	A	N	A
Tympanogram						
N (228)	167	61	132	96	134	94
A (40)	25	15	12	28	18	22
ART						
N (198)	143	55	111	87	114	84
A (70)	49	21	33	37	38	32
DPOAE[a]						
N (24)	18	6	24	0	20	4
P/A (44)	30	14	35	9	34	10
Ab (200)	144	56	85	115	98	102
Tympanogram, ART, and DPOAE combined						
N (24)	18	6	24	0	20	4

Note. ART = acoustic reflex threshold; DPOAEs = distortion product otoacoustic emissions; ABG = air-bone gap; SRT = speech reception threshold; WRS = word recognition scores;
[a] DPOAE findings were classified as normal (N), present but abnormal (P/A), or absent (Ab).

Table 7

Correlation Between PTA$_{0.5-2}$, PTA$_{0.5-4}$, SRT, Age, and WRS

Parameter	PTA$_{0.5-2}$	PTA$_{0.5-4}$	SRT	WRS	Age
PTA$_{0.5-2}$		.94*	.90*	−.53*	.55*
PTA$_{0.5-4}$	.94*		.86*	−.55*	.61*
SRT	.90*	.86*		−.50*	.56*
WRS	−.53*	−.55*	−.50*		−.33*
Age	.55*	.61*	.56*	−.33*	

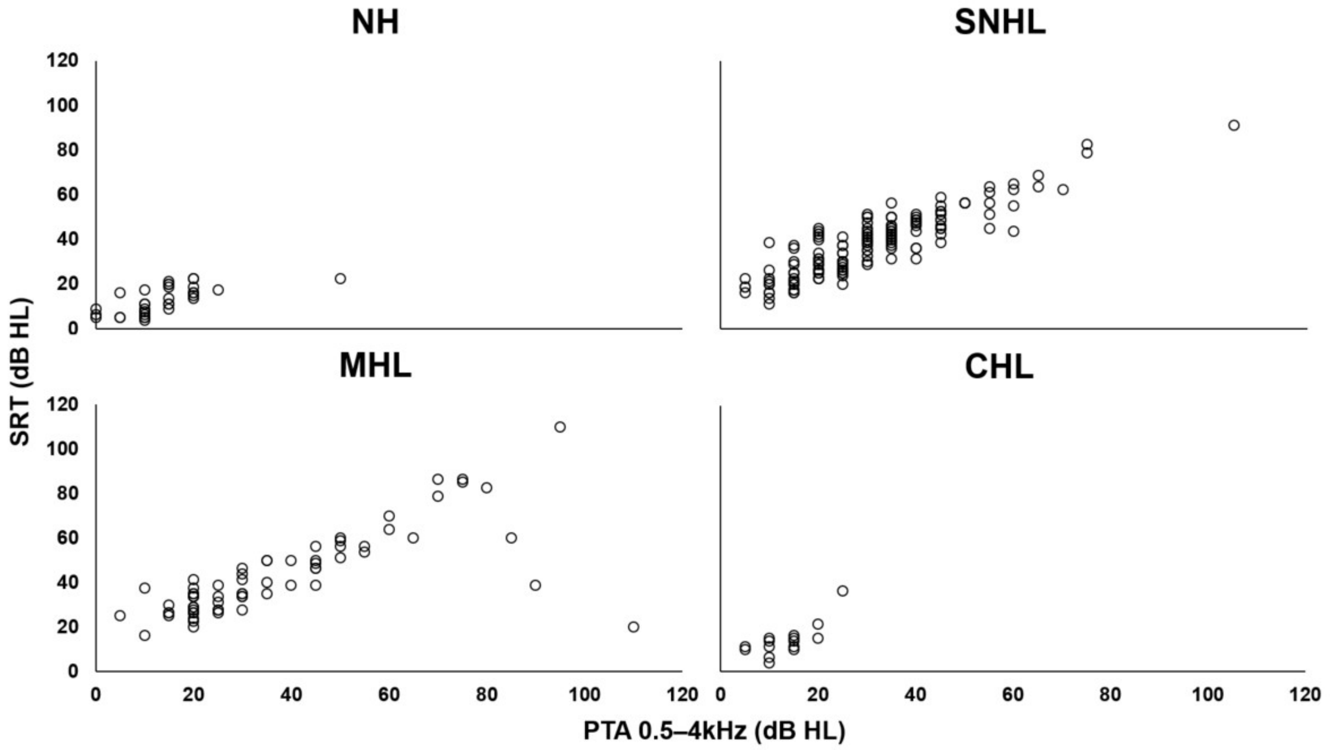
Note. PTA$_{0.5-2}$ = pure-tone average at 500, 1000, and 2000 Hz; PTA$_{0.5-4}$ = pure-tone average at 500, 1000, 2000, 3000, and 4000 Hz; SRT = speech reception threshold; WRS = word recognition score.
*Correlation significant at .01 level (2-tailed).

classified as abnormal if the difference between PTA and SRT was greater than 10 dB. With respect to SRT-PTA$_{0.5-2}$, 29 ears (19 ears sloping configuration) and with respect to SRT-PTA$_{0.5-4}$, 69 ears (60 ears sloping configuration) showed an abnormal relationship.

Discussion

This study analyzed the correlations and disagreements between the different tests used in the standard test battery. Pure-tone audiometry revealed that sensorineural is the most expected hearing loss category, followed by mixed hearing loss, normal hearing, and conductive hearing loss. Regarding the types of hearing loss, our findings were consistent with the reported values (Margolis & Saly, 2008; Tanna et al., 2021). However, among 33 ears diagnosed as normal hearing by pure-tone audiometry, substantial abnormal findings were observed in DPOAE (48.5%), ART (18.2%), and tympanogram examinations (3%), indicating that these tests are more sensitive to middle ear conditions and provide valuable information compared to pure-tone audiometry. Although ABGs are commonly observed in patients with conductive or mixed hearing loss (Scarpa et al., 2020), in our study, ABG alone could not differentiate between participants with and without a history of ear

Figure 2



Type of hearing loss and correlation between SRT and $PTA_{0.5\text{-}4}$

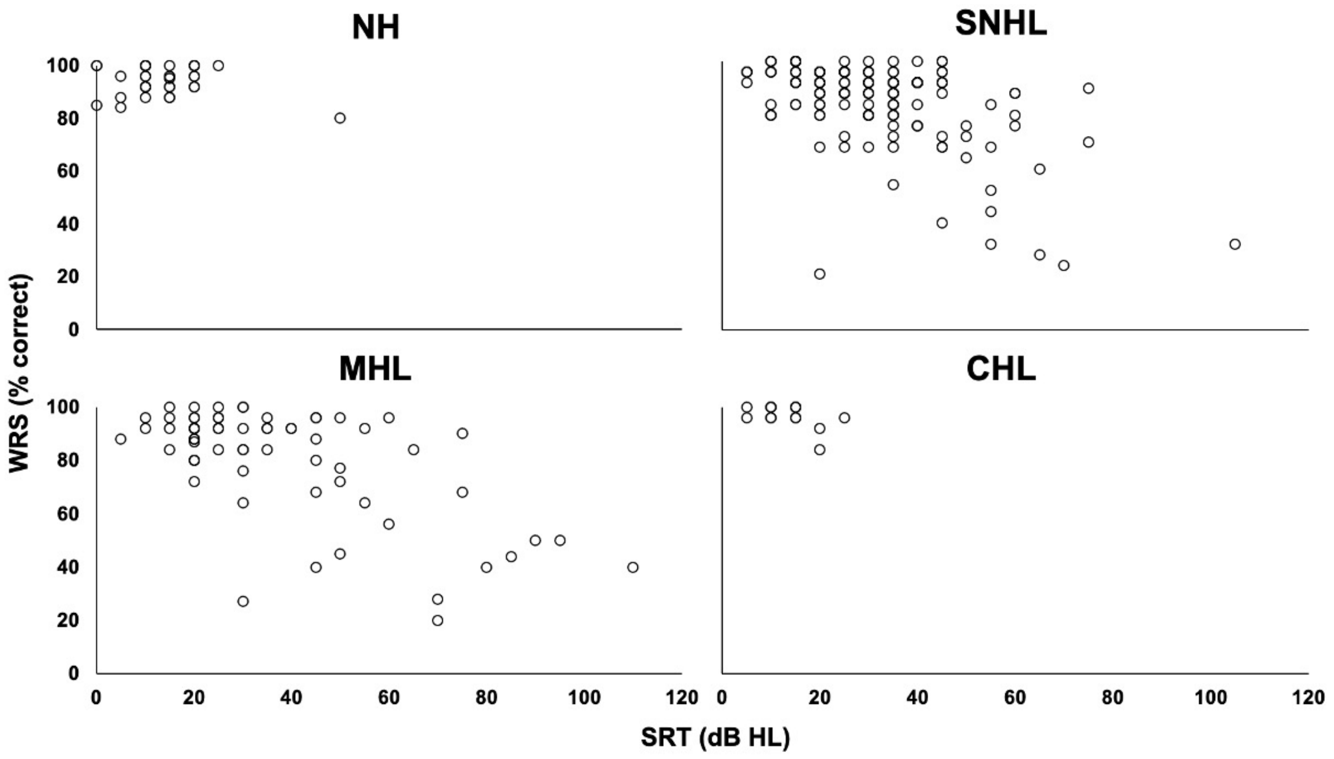
Note. NH = normal hearing; SNHL = sensorineural hearing loss; MHL = mixed hearing loss; CHL = conductive hearing loss; SRT = speech reception threshold; HL = hearing level; $PTA_{0.5\text{-}4}$ = pure-tone average of 500, 1000, 2000, 3000, and 4000 in dB HL.

disorders. Notably, ABG more than 10 dB was present in approximately 25% of patients with normal tympanogram, ART, and DPOAE findings. These results support the opinion that ABG is not the sole predictor of middle ear pathologies (Margolis, 2010; Studebaker, 1967).

With SRT, $PTA_{0.5\text{-}2}$ had a higher correlation coefficient than $PTA_{0.5\text{-}4}$. These findings echo previous findings, in which a higher correlation coefficient between $PTA_{0.5\text{-}2}$ and SRT was reported, and therefore, $PTA_{0.5\text{-}2}$ was claimed to be an adequate estimator of the threshold for speech recognition (Toledo dos Anjos et al., 2014). In particular, SRT in quiet is useful in hearing aid evaluation only if speech material is appropriate to the hearing loss configuration and to the frequency response of amplification (Van Tasell & Yanz, 1987). Overall, SRT had a strong correlation with pure-tone audiometry, and the observed values of the correlation coefficient were in agreement with the reported values (Picard et al., 1999). However, in our study, SRT did not predict the type of hearing loss; in fact, in the case of conductive hearing loss, no patients had an abnormal SRT. For sensorineural and mixed hearing losses, 40% of the patients had normal SRT.

A weak negative correlation between PTA and WRS was consistent with previous findings (Toledo dos Anjos et al., 2014). WRS did not classify hearing as abnormal in a different type of hearing loss, and the median correct WRS was more than 90% in conductive and sensorineural hearing loss and close to 90% in mixed hearing loss. Thus, these results indicate that, as a standard component of the audiological test battery, WRS does not add much diagnostic value. Likewise, SRTs are generally used to cross-check pure-tone audiometry findings; our results suggest that if the testing is done for adults with reliable audiometric responses, SRT in quiet adds little value to assessing the severity and type of hearing loss. Due to the diversity of auditory dysfunctions and the limitations of individual tests, the audiological test battery generally includes a mix of tests. However, some of these tests may have limited diagnostic value in several cases (Margolis & Saly, 2008). For example, most audiologists use AC, BC,

Figure 3



Type of hearing loss and correlation between SRT and WRS

Note. NH = normal hearing; SNHL = sensorineural hearing loss; MHL = mixed hearing loss; CHL = conductive hearing loss; SRT = speech reception threshold; WRS = word recognition score; HL = hearing level.

SRT, and WRS in comprehensive evaluation (Stephens, 2018; Swanson, 2012). Based on the findings of the current study and the available literature, we provide the following recommendations to optimize the number of tests for specific scenarios.

Recommendations

In the diagnostic test battery for middle ear abnormalities, we recommend replacing BC, SRT, and WRS with tympanometry, ART, and DPOAE. In our assessment, with these replacements, audiologists can make more productive use of resources. More specifically, we recommend:

1. Participants with no history of ear disorders and with normal ARTs, tympanogram, and DPOAEs do not require a BC test to examine the conductive component.
2. Participants without a history of ear disorders, with bilaterally sloping hearing loss, and with mixed results – one test within normal limits and one abnormal – do not need a BC test.
3. SRT is not necessary for participants with normal DPOAEs and participants with bilateral sloping hearing loss (age < 65 years).
4. WRS in quiet at one presentation level does not add value for most patients.

The above recommendations can help optimize the resources and time typically involved in hearing assessment; however, further studies are needed to validate and extend these recommendations. The following limitations must also be acknowledged when interpreting our results.

Limitations

The findings of this study support the need to follow a more evidence-based approach to diagnostic audiology. This study made a strong case for using a case-specific and evidence-based approach in hearing assessment. The foremost limitation is the retrospective study design. A prospective study with well-defined objectives could more effectively examine the efficacy of a standard audiological test battery. Most notably, the fairly small pediatric population in our study necessitates additional confirmation with regard to this demographic. Furthermore, in our study, no subgroup analysis was performed with respect to sex, age, and other demographic variables; such an analysis could be helpful in making more specific recommendations. Finally, although we have given several recommendations for a structured assessment of hearing, we have not quantified the diagnostic efficacy under different scenarios. Another challenge in quantitative evaluation of the characteristics of cumulative diagnostic effectiveness is the absence of comparable gold standards for tests included in the standard audiological test battery. Future studies should focus on examining these aspects in more detail.

Conclusions

The current study investigated the clinical utility of tests commonly included in the standard audiological test battery. Our findings suggest that, in several cases, BC, SRT, and WRS do not offer substantial utility as part of the standard audiological test battery. None of the individuals with conductive hearing loss were found to have an abnormal SRT. SRT had a moderate correlation and WRS had a low correlation with the degree of hearing loss. To optimize the time and cost associated with audiological testing, it is essential to select a test or combination of tests with the highest clinical utility. In essence, our research indicates that, with careful consideration for the patient's needs, the use of tympanometry, ART, and DPOAE in lieu of BC, SRT, and WRS will boost the effectiveness of the standard audiological test battery. The findings of this study will help develop a more effective framework for hearing assessments.

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Disclosures

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