Pure-tone audiometry without bone-conduction thresholds: using the digits-in-noise test to detect conductive hearing loss

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Abstract

Objective: COVID-19 has been prohibitive to traditional audiological services. No- or low-touch audiological assessment outside a sound-booth precludes test batteries including bone conduction audiometry. This study investigated whether conductive hearing loss (CHL) can be differentiated from sensorineural hearing loss (SNHL) using pure-tone air conduction audiometry and a digits-in-noise (DIN) test.

Design: A retrospective sample was analysed using binomial logistic regressions, which determined the effects of pure tone thresholds or averages, speech recognition threshold (SRT), and age on the likelihood that participants had CHL or bilateral SNHL.

Study sample: Data of 158 adults with bilateral SNHL ($n = 122$; $\text{PTA}_{0.5\text{–}4\text{ kHz}} > 25$ dB HL bilaterally) or CHL ($n = 36$; air conduction $\text{PTA}_{0.5\text{–}4\text{ kHz}} > 25$ dB HL and ≥20 dB air bone gap in the affected ears) were included.

Results: The model which best discriminated between CHL and bilateral SNHL used low-frequency pure-tone average (PTA), diotic DIN SRT, and age with an area under the ROC curve of 0.98 and sensitivity and specificity of 97.2 and 93.4%, respectively.

Conclusion: CHL can be accurately distinguished from SNHL using pure-tone air conduction audiometry and a diotic DIN. Restrictions on traditional audiological assessment due to COVID-19 require lower touch audiological care which reduces infection risk.

Keywords: COVID-19; coronavirus; audiometry; digits-in-noise; speech-in-noise; speech recognition threshold

Introduction

The COVID-19 pandemic and its sudden requirement for physical distancing is prohibitive to traditional models of contact-based audiological service delivery. According to US Centres for Disease Control and Prevention (CDC) guidelines, traditional audiological services are a medium to high-risk for COVID-19 infection due to the test setup, patient proximity and length of consultations (Centers for Disease Control and Prevention 2020). Furthermore, the largest demographic requiring audiological services are people over 60 years of age or those medically vulnerable (e.g. diabetes, cardiac-related illnesses, etc.) who are at the highest risk of COVID-19 related mortality and morbidity (Grasselli et al. 2020). As is the case for many health disciplines globally, COVID-19 is accelerating the use of digital technologies and remote care options that are changing hearing health care delivery modes (Keesara, Jonas, and Schulman 2020). While being able to support existing patients remotely through telehealth, alternative methods to assess new patients will become increasingly important as the COVID-19 pandemic is likely to persist into 2021 and beyond (Gates 2020).

Audiological assessments for hearing loss traditionally consist of a face-to-face consultation with a trained professional. Pure tone air and bone conduction audiometry are the gold standards to determine the degree, configuration, and type of hearing loss. However, audiological care that offers minimal physical interactions is currently necessary as an option to safely provide care to vulnerable populations (Swanepoel and Hall 2020). Such services may be defined as being *low-touch*, where face-to-face contact between client and audiologist is reduced or could even be *no-touch*, where home-based tests and treatment options could be provided (Swanepoel and Hall 2020). A specific challenge with low- or no-touch models, however, is to differentiate persons with purely sensorineural hearing loss (SNHL) from those with conductive hearing loss (CHL) or possible ear disease who require medical and comprehensive audiological assessment (Swanepoel and Hall 2020). When sensorineural hearing loss can be confirmed, air conduction thresholds may be sufficient to prescribe and fit a hearing aid which can be measured in a number of low-touch ways (Swanepoel and Hall 2020).

Traditionally CHL or mixed hearing loss is detected and characterised by air- and bone-conduction audiometry, with the difference between these thresholds (i.e. the air-bone gap, ABG) indicating the severity of the conductive component. However, to obtain a reliable assessment of bone conduction thresholds, which can be measured down to −10 dB HL, a sound-treated booth is required. Unoccluded bone conduction audiometry requires maximum sound attenuation of at least a single-walled sound booth (International Standards Organization 2015). Pure tone air conduction, on the other hand, can reliably be measured outside a sound-booth in controlled environments using applications that, in some cases, monitor ambient noise (Sandström et al. 2016; Swanepoel et al. 2019). Before considering amplification in CHL cases, a medical assessment, and possible intervention, is recommended. The incidence of CHL relative to SNHL in adults is very low, with a recent report indicating it is 2% in people over 70 years of age (Hoff et al. 2020). A small ABG sub-group of patients suspected of having a CHL, therefore, requires standard sound-booth based audiological assessment and subsequent medical evaluation. Sound-booth testing, to accommodate for bone conduction audiometry, is especially challenging during the COVID-19 pandemic due to increased infection risk in confined environments with limited air circulation (Stadnytskyi et al. 2020). Furthermore, bone conduction audiometry requires skilled personnel to set-up and test, while self-testing is associated with higher variability

(Margolis et al. 2010) and poorer reliability (Swanepoel and Biagio 2011) than professional testing, especially at lower frequencies.

Where situational limitations like COVID-19 prevent the measurement of bone conduction thresholds in a sound booth, alternative means to determine an ABG could triage care for pure SNHL cases from those with potential CHL or ear disease. Tympanometry and tuning fork tests may supplement pure tone audiometry to indicate possible CHL (Silman and Silverman 1997) but rely on additional equipment and trained personnel to complete. Other options to detect ear disease include questionnaires, such as the Consumer Ear Disease Risk Assessment (CEDRA) which has a sensitivity of greater than 90% (Klyn et al. 2019). A novel test method by Convery et al. (2014) used a combination of automated pure-tone air conduction audiometry and a tone-in-noise task to estimate the presence and size of ABG at different test frequencies. The prediction had fairly high accuracy, being more accurate with larger ABGs and at lower test frequencies. Furthermore, the prediction had a sensitivity of 80% and specificity of 77% at any ABG size if the threshold in quiet and signal-to-noise ratio (SNR) were known at 0.5 and 1 kHz. In the current study, we explored a shorter procedure using a combination of speech-in-noise testing and pure tone air conduction audiometry to screen for and distinguish between CHL and SNHL.

The digits-in-noise (DIN) test has become a popular hearing screening procedure, available directly to the public as a web- or smartphone application (Smits and Houtgast 2005; De Sousa et al. 2020; Potgieter et al. 2015; Potgieter et al. 2018). This self-administered test measures the ability to accurately recognise 50% of spoken digit triplets in the presence of speech-weighted masking noise (speech recognition threshold; SRT expressed in dB SNR). While both CHL and SNHL have elevated pure tone thresholds in quiet compared to normal-hearing listeners, hearing loss due to cochlear damage typically presents with reduced frequency selectivity. Frequency selectivity relates to the ability of the auditory system to distinguish components of a complex sound (such as speech in noise) and is measured through psychophysical tuning curves. Ears with normal cochlear functioning, such as normal hearing or CHL, have psychophysical tuning curves that are sharper resulting in improved frequency selectivity (Moore 1996), whereas the tuning curves are flatter with cochlear damage. As a result, the sensitivity and specificity of the DIN to detect SNHL is high (>80%) (Smits, Kapteyn, and Houtgast 2004; Potgieter et al. 2018). However, the test traditionally is insensitive to detect CHL, since the attenuation caused by CHL affects the audibility of both digits and noise about equally at suprathreshold intensities (De Sousa et al. 2020). Thus, listeners with elevated air conduction thresholds may have relatively good SRTs when the hearing loss is conductive (Smits, Kapteyn, and Houtgast 2004).

Since traditional bone conduction audiometry in a sound booth may be contraindicated for vulnerable populations during the COVID-19 pandemic, the main objective of this study was to determine if it is possible to accurately distinguish CHL from SNHL with the administration of pure tone air conduction thresholds and a diotic DIN test. Using air conduction tests only could enable audiological care options with minimal (low-touch) or no physical (no-touch) contact. Our hypothesis was that people with CHL would present with normal or near-normal DIN SRTs, but with elevated pure-tone air conduction thresholds, whereas those with purely SNHL would have both elevated DIN SRTs and pure tone air conduction thresholds.

Method

This study received ethical approval from the Humanities Research Ethics Committee, University of Pretoria (protocol number: HUM003/0120).

Participants

The study was embedded as part of a normative DIN study at the University of Pretoria (Pretoria, South Africa). Data collection was conducted from June 2017 to September 2019. An additional 6 cases were added from a dataset completed in 2015. Participants were tested at multiple sites, where they were attending appointments at a hospital or university clinic or private audiology practice. This retrospective study pooled data from 158 adult cases between the ages of 18 and 92 years (mean = 61 years, SD = 17 years). Criteria for inclusion in the dataset were participants with bilateral sensorineural hearing loss ($n = 122$; $\text{PTA}_{0.5\text{–}4\ \text{kHz}} >$ 25 dB HL bilaterally) or CHL ($n = 36$; air conduction $\text{PTA}_{0.5\text{–}4\ \text{kHz}} >$ 25 dB HL and ≥20 dB ABG in the affected ears). In the CHL group, bone conduction PTA did not exceed 25 dB HL, except for one bilaterally symmetric mixed hearing loss case where the bone conduction PTA in the poorer ear was 34 dB HL indicating a mixed hearing loss with mild CHL component. There were 15 bilateral and 21 unilateral CHL cases.

Procedures and equipment

Tone audiometry was conducted by an audiologist as part of the selection protocol. Testing was done at various sites using audiometers calibrated to industry standards. The modified Hughson–Westlake method was used to determine pure-tone air and bone conduction thresholds (Hughson and Westlake 1944). In addition, the South African English DIN test was conducted by the participants on a Samsung Trend Neo smartphone coupled with manufacturer supplied wired earbuds, or Sennheiser HDA 220 headphones. Since Potgieter et al. (2015) showed no difference between the DIN SRTs across five headphone types, it was not expected that this choice of headphone type would influence results. A detailed description of the DIN test procedure and stimuli is outlined in De Sousa et al. (2020). In summary, the test uses an adaptive one-up, one-down test procedure. Stimuli are binaurally same-phased (diotic) and digits are presented with speech weighted masking noise to determine the signal to noise ratio (SNR) at which 50% of digit triplets (e.g. 2-4-7) can be correctly recognised, the speech recognition threshold (SRT), determined by averaging the SNR of the last 19 of 23 digit triplets. Diotic presentation was not expected to have a large influence on SRTs of participants with either unilateral or bilateral CHL, since the attenuation caused by CHL affects the audibility of both digits and noise equally (De Sousa et al. 2020).

Statistical analysis

Binomial logistic regressions were constructed to ascertain the effects of age, pure tone thresholds or PTA, and SRT on the likelihood that participants had CHL or bilateral SNHL. Linearity of the continuous variables with respect to the logit of the dependent variable was assessed via the Box-Tidwell (1962) procedure. A Bonferroni correction was applied when using all terms in the model, resulting in statistical significance being accepted when $p < 0.01$ (Tabachnick and Fidell 2014). Based on this assessment, all continuous independent variables were found to be linearly related to the logit of the dependent variable (i.e. CHL/bilateral SNHL). There was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1. Furthermore, there were no residuals deviating more than 3 standard deviations from the mean. Using these probability equations, category prediction (CHL vs SNHL) was evaluated on the study sample. Receiver operating characteristic (ROC) curves were generated to determine cut-points for optimal sensitivity and specificity for each model. Furthermore, positive predictive values (the percentage of correctly predicted CHL cases compared to the total number of cases predicted as having CHL) and negative predictive values (the percentage of correctly predicted cases with SNHL compared to the total number of cases predicted as not having SNHL) were modelled for different prevalence rates of CHL.

Results

Sample demographics, pure tone averages (PTA) and diotic DIN test performance can be seen in Table 1. Frequency specific audiometric thresholds for CHL and bilateral SNHL are presented in Figure 1. The mean age for the CHL group was significantly lower than for the bilateral SNHL group ($t[36.97] = 8.786$, $p < 0.001$).

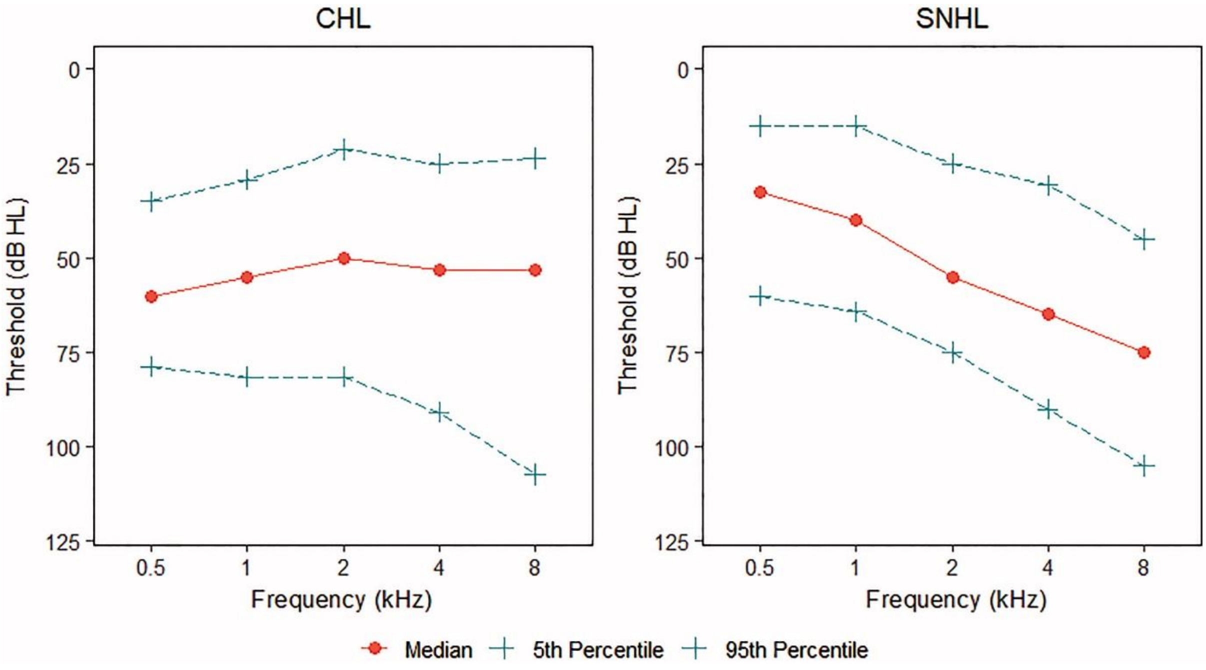

Figure 1. Audiometric thresholds of the poorer ear for participants in the bilateral SNHL (right) and CHL (left) groups.

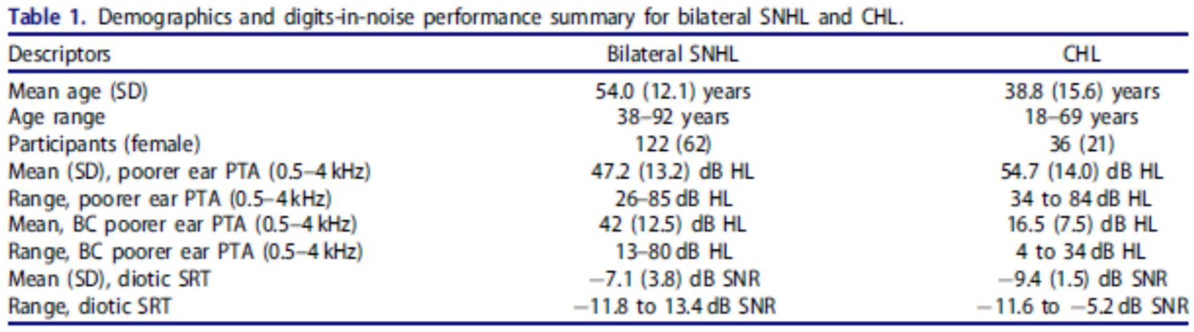

Table 1. Demographics and digits-in-noise performance summary for bilateral SNHL and CHL.

Descriptors	Bilateral SNHL	CHL
Mean age (SD)	54.0 (12.1) years	38.8 (15.6) years
Age range	38–92 years	18–69 years
Participants (female)	122 (62)	36 (21)
Mean (SD), poorer ear PTA (0.5–4 kHz)	47.2 (13.2) dB HL	54.7 (14.0) dB HL
Range, poorer ear PTA (0.5–4kHz)	26–85 dB HL	34 to 84 dB HL
Mean, BC poorer ear PTA (0.5–4 kHz)	42 (12.5) dB HL	16.5 (7.5) dB HL
Range, BC poorer ear PTA (0.5–4 kHz)	13–80 dB HL	4 to 34 dB HL
Mean (SD), diotic SRT	−7.1 (3.8) dB SNR	−9.4 (1.5) dB SNR
Range, diotic SRT	−11.8 to 13.4 dB SNR	−11.6 to −5.2 dB SNR

The relationship between diotic SRT and individual test frequencies for bilateral SNHL and CHL are presented in Figure 2. Diotic SRTs were lower (better) for CHL than SNHL for each single test frequency. The same was found when considering pure tone averages (either averaged over 0.5–4 kHz, low frequencies 0.5 and 1 kHz or high frequencies (2 and 4 kHz) and diotic SRT (Figure 3). The probability of a participant having CHL or bilateral SNHL was determined using various models of binomial regressions. Model summaries with and without age as a predictor are in Tables 2 and 3, respectively. Models including low frequency PTA (0.5 and 1 kHz) accounted for most of the variance in CHL, had the highest accurate category prediction, and showed the largest area under the receiver operating characteristic curve (AUROC; Figure 4). The low frequency PTA (0.5 and 1 kHz) and age model differentiated CHL from bilateral SNHL with an overall accuracy of 93.7% and sensitivity and specificity of 97.2 and 93.4%, respectively. The model equation uses the average air conduction threshold of 0.5 and 1 kHz in the poorer ear, diotic SRT and age:

$$p = \frac{1}{1 + \exp\left[-\left((-8.100) + (0.140 \times LFPTA) + (-0.848 \times Diotic\ \ SRT) + (-0.125 \times Age)\right)\right]}$$

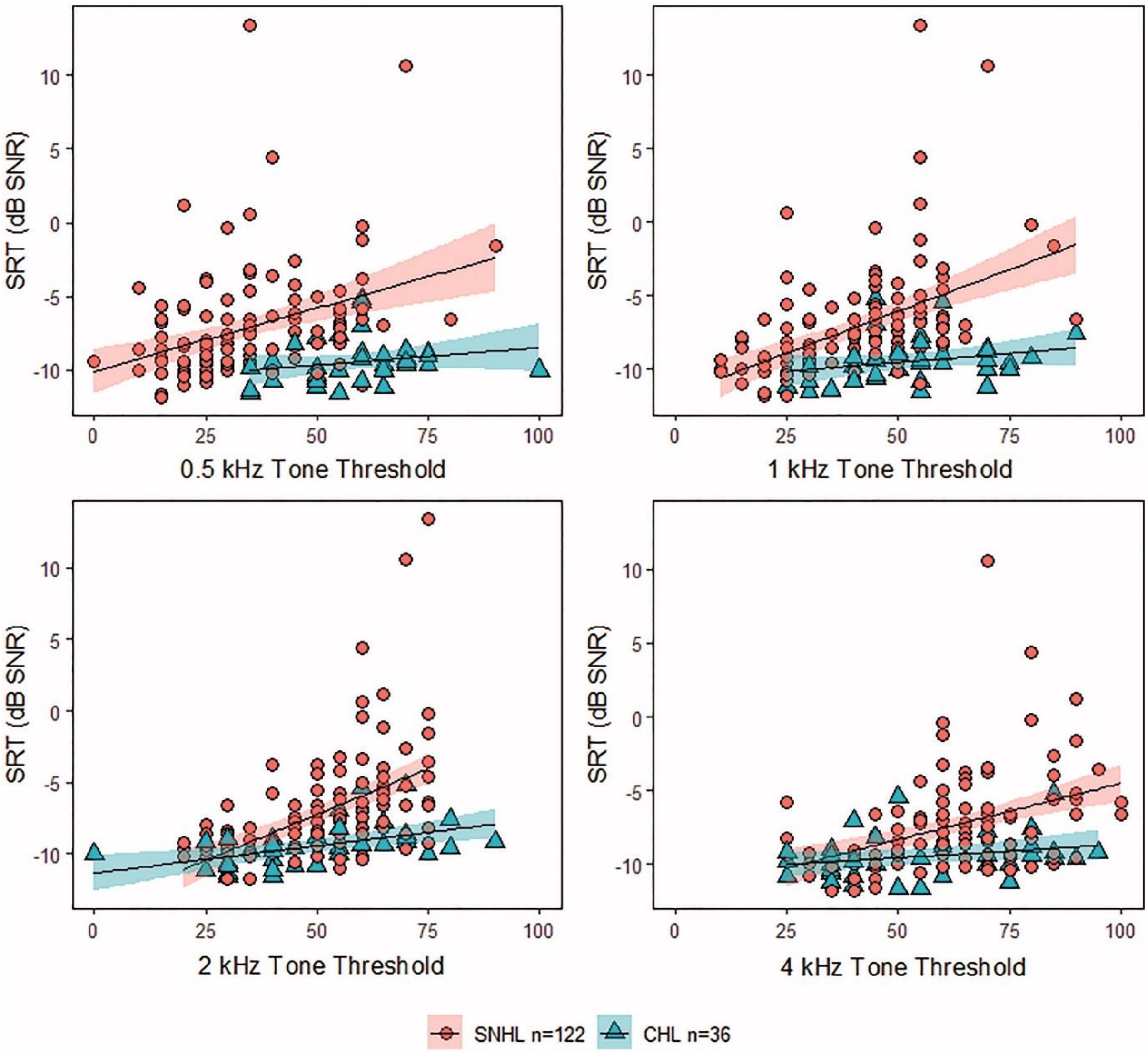

Figure 2. Diotic SRT across individual poorer ear frequency thresholds for bilateral SNHL and CHL. The lines are linear regression lines fit to either bilateral SNHL or CHL data. The shading indicates 95% confidence intervals.

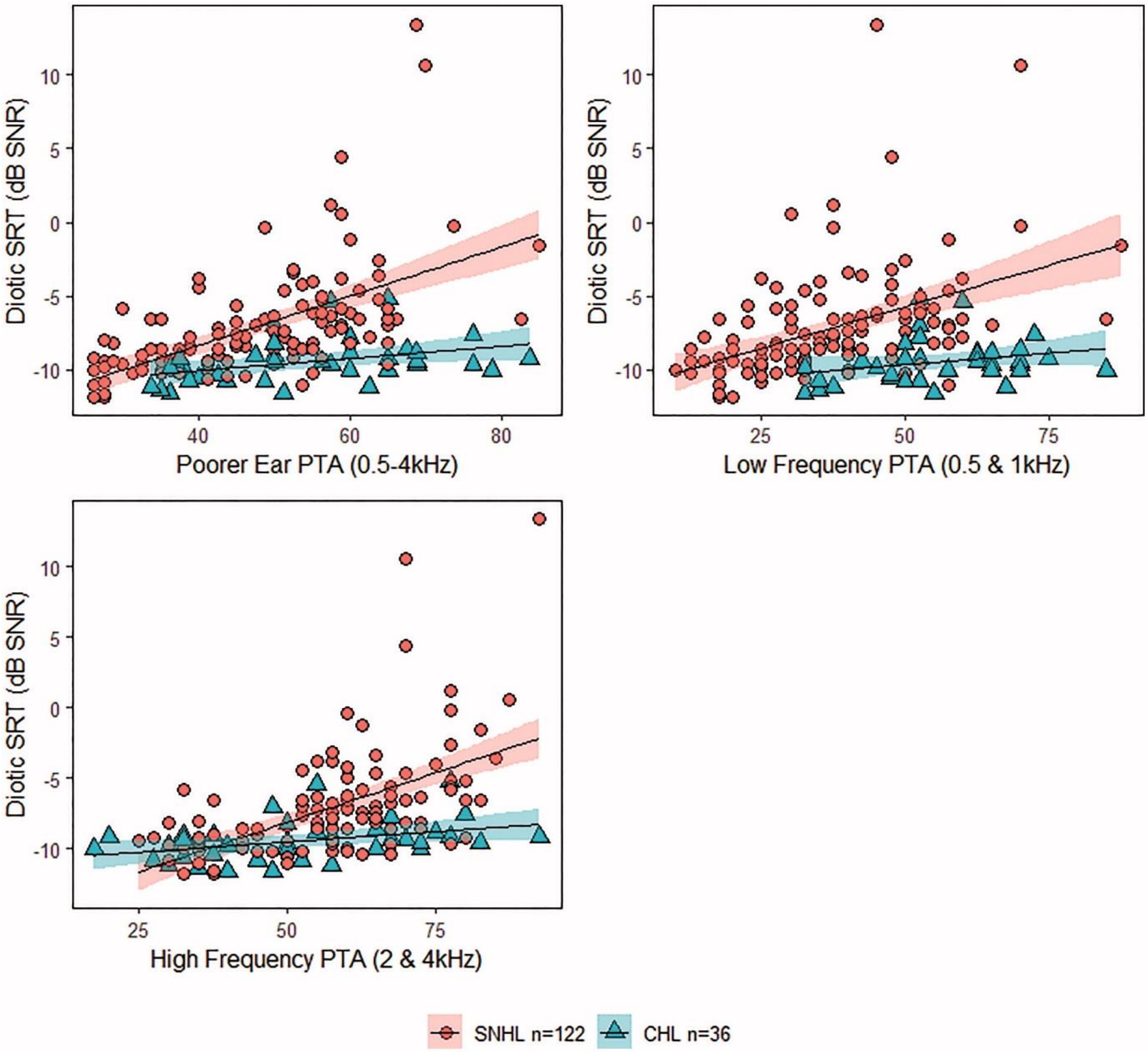

Figure 3. Diotic SRT across poorer ear PTA (0.5–4 kHz), low frequency PTA (0.5 and 1 kHz) and high frequency PTA (2 and 4 kHz) for bilateral SNHL and CHL. The lines are linear regression lines fit to either bilateral SNHL or CHL data. The shading indicates 95% confidence intervals.

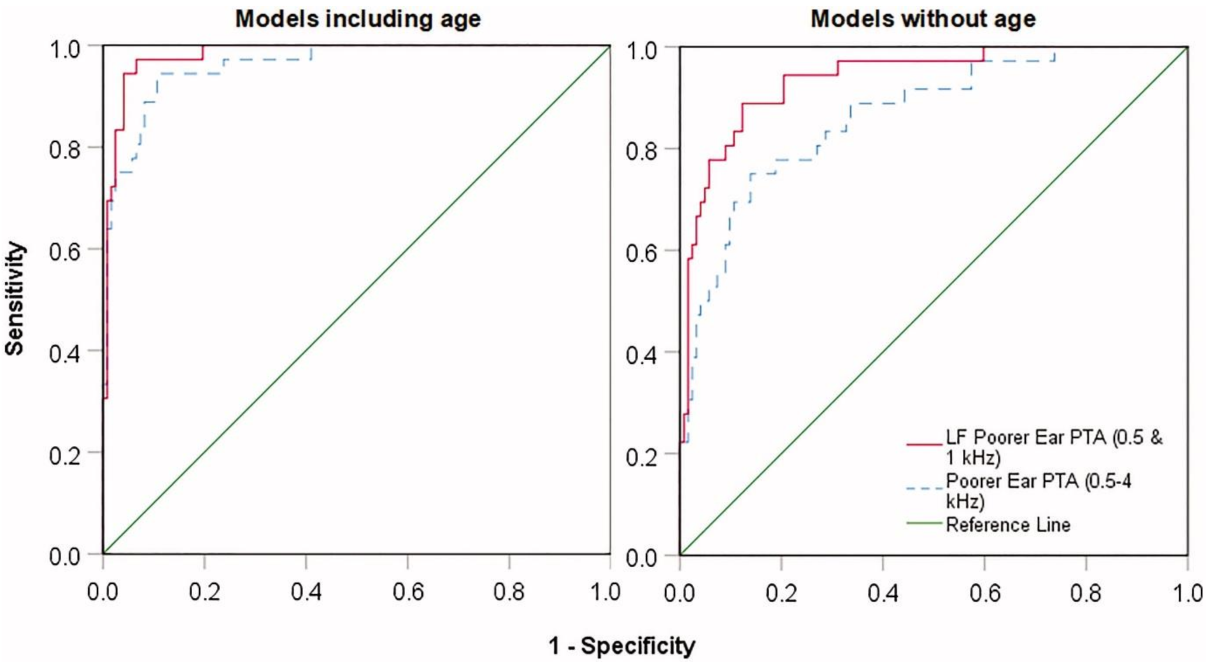

Figure 4. Receiver operating characteristic curve for discriminating CHL from SNHL for LF PTA (0.5 and 1 kHz) compared to poorer ear PTA (0.5–4 kHz), with and without age as a predictor.

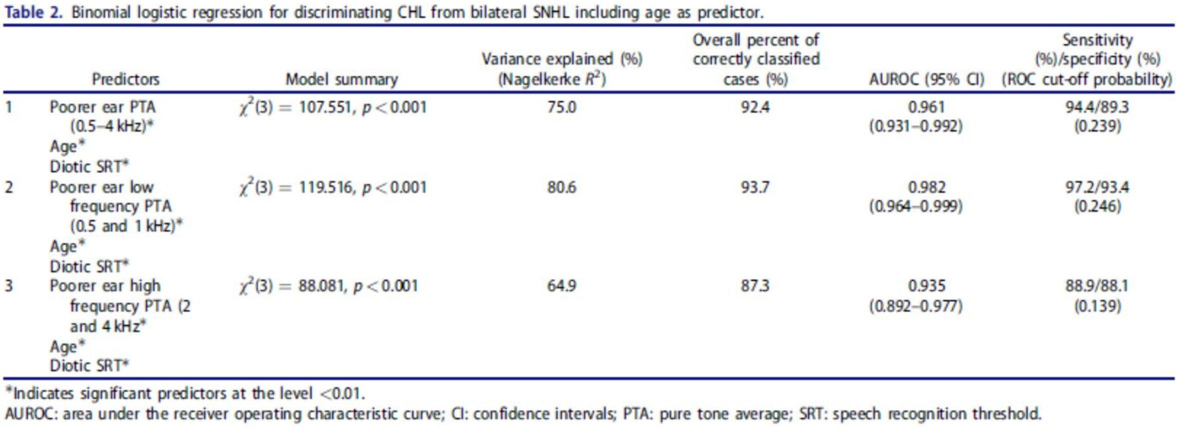

Table 2. Binomial logistic regression for discriminating CHL from bilateral SNHL including age as predictor.

	Predictors	Model summary	Variance explained (%) (Nagelkerke R^2)	Overall percent of correctly classified cases (%)	AUROC (95% CI)	Sensitivity (%)/specificity (%) (ROC cut-off probability)
1	Poorer ear PTA (0.5–4 kHz)* Age* Diotic SRT*	$\chi^2(3) = 107.551$, $p < 0.001$	75.0	92.4	0.961 (0.931–0.992)	94.4/89.3 (0.239)
2	Poorer ear low frequency PTA (0.5 and 1 kHz)* Age* Diotic SRT*	$\chi^2(3) = 119.516$, $p < 0.001$	80.6	93.7	0.982 (0.964–0.999)	97.2/93.4 (0.246)
3	Poorer ear high frequency PTA (2 and 4 kHz* Age* Diotic SRT*	$\chi^2(3) = 88.081$, $p < 0.001$	64.9	87.3	0.935 (0.892–0.977)	88.9/88.1 (0.139)

*Indicates significant predictors at the level <0.01.
AUROC: area under the receiver operating characteristic curve; CI: confidence intervals; PTA: pure tone average; SRT: speech recognition threshold.

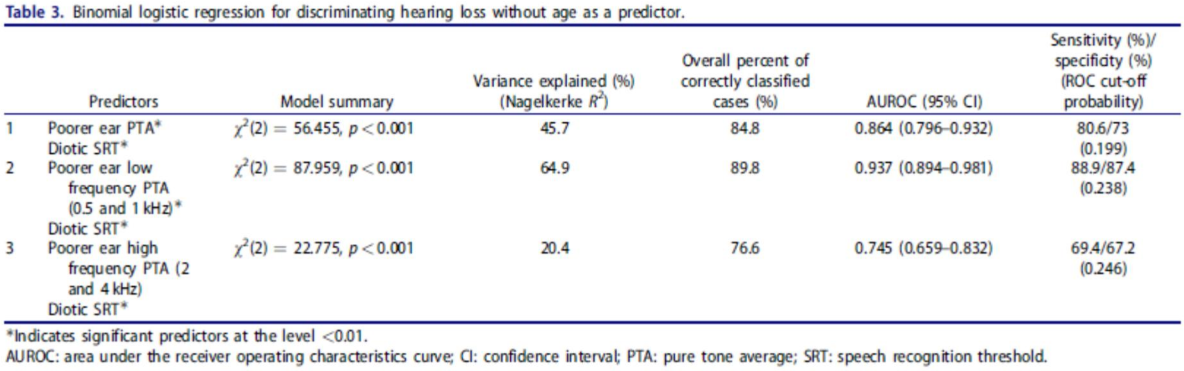

Table 3. Binomial logistic regression for discriminating hearing loss without age as a predictor.

	Predictors	Model summary	Variance explained (%) (Nagelkerke R^2)	Overall percent of correctly classified cases (%)	AUROC (95% CI)	Sensitivity (%)/specificity (%) (ROC cut-off probability)
1	Poorer ear PTA* Diotic SRT*	$\chi^2(2) = 56.455$, $p < 0.001$	45.7	84.8	0.864 (0.796–0.932)	80.6/73 (0.199)
2	Poorer ear low frequency PTA (0.5 and 1 kHz)* Diotic SRT*	$\chi^2(2) = 87.959$, $p < 0.001$	64.9	89.8	0.937 (0.894–0.981)	88.9/87.4 (0.238)
3	Poorer ear high frequency PTA (2 and 4 kHz) Diotic SRT*	$\chi^2(2) = 22.775$, $p < 0.001$	20.4	76.6	0.745 (0.659–0.832)	69.4/67.2 (0.246)

*Indicates significant predictors at the level <0.01.
AUROC: area under the receiver operating characteristics curve; CI: confidence interval; PTA: pure tone average; SRT: speech recognition threshold.

Without age the model equation was:

$$p = \frac{1}{1 + \exp\left[-\left(\left(-16.277\right) + \left(-0.142 \times LFPTA\right) + \left(-0.988 \times Diotic\ \ SRT\right)\right)\right]}$$

Positive and negative predictive values modelled for various CHL prevalence rates are presented in Table 4. Across varying prevalence rates, the negative predictive value remained fairly constant (96.9–99.9%), while positive predictive value became substantially higher with an increase in CHL prevalence.

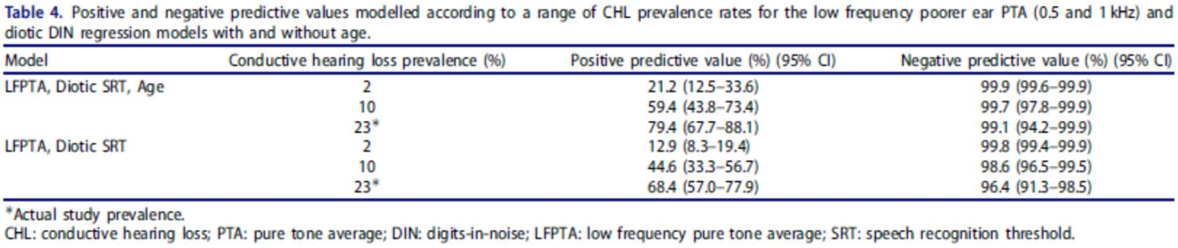

Table 4. Positive and negative predictive values modelled according to a range of CHL prevalence rates for the low frequency poorer ear PTA (0.5 and 1 kHz) and diotic DIN regression models with and without age.

Model	Conductive hearing loss prevalence (%)	Positive predictive value (%) (95% CI)	Negative predictive value (%) (95% CI)
LFPTA, Diotic SRT, Age	2	21.2 (12.5–33.6)	99.9 (99.6–99.9)
	10	59.4 (43.8–73.4)	99.7 (97.8–99.9)
	23*	79.4 (67.7–88.1)	99.1 (94.2–99.9)
LFPTA, Diotic SRT	2	12.9 (8.3–19.4)	99.8 (99.4–99.9)
	10	44.6 (33.3–56.7)	98.6 (96.5–99.5)
	23*	68.4 (57.0–77.9)	96.4 (91.3–98.5)

*Actual study prevalence.
CHL: conductive hearing loss; PTA: pure tone average; DIN: digits-in-noise; LFPTA: low frequency pure tone average; SRT: speech recognition threshold.

Discussion

CHL can be distinguished from bilateral SNHL with high accuracy using a combination of pure tone air conduction audiometry and a diotic DIN test. The degree of accuracy varies depending on (i) whether age is used as a predictor, and (ii) the audiometric frequencies used, with a low-frequency PTA (0.5 and 1 kHz) outperforming a four frequency PTA (0.5–4 kHz) and high-frequency PTA (2 and 4 kHz) PTA. The average age in the CHL group was substantially lower than the SNHL group, which meant that including age in the prediction improved model accuracy. The CHL group constituted only 23% of the study sample and is not necessarily representative of the larger population of adult CHL cases. Age-related SNHL has a reasonably predictable onset and progression across a large cohort (Cruickshanks et al. 1998; Roth, Hanebuth, and Probst 2011, Homans et al. 2017), whereas CHL in adults is not typically age-related and is likely to have a larger spread and lower mean age when compared to typical SNHL. Nevertheless, the model accuracy remained high, even without age as a predictor, with outstanding AUROC (0.94; Mandrekar 2010) and sensitivity and specificity around 90%.

Although bone conduction audiometry remains the gold standard to determine a conductive component, it poses a number of limitations including significant variability and calibration standard errors (Margolis et al. 2013). In controlled experimental procedures, the typical standard deviation for bone conduction audiometry was reported around 8 dB, while an intermediate standard deviation of 6 dB was found for the associated ABG (Robinson and Shipton 1982; Coles, Lutman, and Robinson 1991). These determinations were under laboratory conditions where the major factor was inherent variation among test administrators (Robinson and Shipton 1982). It is plausible that additional variability may be caused by listener responses. In clinical practice, this variability will likely be higher (Robinson and Shipton 1982). The high sensitivity and specificity of 97.2 and 93.4% for the prediction model using low-frequency PTA and age found in this study is, therefore, particularly appealing as a screening measure to detect conductive hearing loss.

Convery et al. (2014) performed the only other study we could identify to use air-conduction pure tone thresholds to detect and quantify the degree of a conductive component. They administrated an automatic test battery comprising pure tones in quiet and another measure evaluating the lowest SNR at which pure tones could be detected in spectrally and temporally modulated narrowband noise. Using this combination of tests, Convery et al. (2014) obtained reasonably high sensitivity and specificity of 80 and 77% to identify CHL with any ABG size. For ABGs larger than 35 dB, the sensitivity and specificity of their model could improve up to 98 and 80%, respectively. The combined sensitivity and specificity for the prediction model in the current study were higher than those reported by Convery et al. (2014). Convery et al. (2014), however, included a mixed hearing loss in their sample whereas the current study used only pure CHL apart from one mixed hearing loss case, a limitation of this study. Although the participant with mixed hearing loss was identified with CHL in the prediction, the accuracy of this model on varying degrees of mixed hearing loss should be investigated in the future.

Conductive hearing loss prevalence rates may differ across populations (Moore 1999; Hoff et al. 2020; Kaplan et al. 1973; Liu et al. 2001). Results of one study cannot be generalised beyond the population of participants studied because of differences in referral patterns, access to medical care, tendency to seek medical care, and other unknown factors that affect the composition of the groups (Moore 1999). Recent reports in high-income countries confirm that the prevalence of conductive pathology in adult populations with hearing loss is low, with reports between 2 and 5% (Klyn et al. 2019; Hoff et al. 2020). Positive and negative predictive values in the current study were modelled according to various disease prevalence estimates (Table 4) for illustrative purposes. Using the prediction model with age, positive predictive value was higher compared to the model without age, particularly at higher prevalence rates.

The major clinical application of the prediction model proposed in this study serves to differentiate adult hearing losses at risk of an ABG requiring further medical and audiological examination. This type of approach can enable alternative audiological service provision outside of traditional settings (i.e. sound booth) where bone conduction audiometry and other tests are typically conducted to confirm a CHL. Where traditional sound-booth clinical assessments may not be indicated, as in the case of the current COVID-19 pandemic (Swanepoel and Hall 2020), this approach could prioritise patients who require further medical and audiological assessment whilst providing hearing aids based on air conduction tests for individuals with no conductive hearing loss risk. Considering the low prevalence of CHL compared to SNHL in adults (Hoff et al. 2020), the vast majority of patients with hearing loss could benefit from alternative low-touch models of audiological care that exclude bone conduction testing. We show here that these models could be used effectively towards treatment with hearing aids for vulnerable patients during COVID-19 (Swanepoel and Hall 2020). This approach also has potential for other clinical applications including for resource-constrained settings in low- and middle-income countries where diagnostic audiometry with bone conduction may be unavailable.

Future study of this air conduction test approach to differentiate CHL and SNHL in paediatric populations is warranted. CHL is more prevalent among children due to a higher rate of otitis media and Eustachian tube dysfunction. Already, the validity and reliability of a DIN test have been shown in children as young as 4 years (Koopmans, Goverts, and Smits 2018). This model may thus have further application in school screening programmes which are regularly conducted in high ambient noise levels which impede accurate bone-conduction testing (McPherson, Law, and Wong 2010).

Conclusions

The findings of this study show that CHL can be distinguished from SNHL using a combination of pure-tone air-conduction thresholds and a diotic DIN with very good accuracy and high sensitivity and specificity. Considering restrictions on traditional audiological assessments due to an infectious disease like COVID-19, alternative methods that enable audiological care with minimal physical contact may reduce mortality and infection risk whilst optimising care pathways and resource allocation. While this prediction model may have several potential applications, including for resource-constrained settings, it provides a timely solution to the current need for low- and no-touch models of audiological service delivery.

Disclosure statement

DWS, DRM, and HCM have a relationship with the hearX Group which includes equity, consulting, and potential royalties. This research may contribute to hearX Group products.

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