Supra-aural transducer-related artifact contributes to overestimation of noise-induced hearing loss

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Supra-aural transducer-related artifact contributes to overestimation of noise-induced hearing loss (L)

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This study compared the effects of supra-aural and insert receivers on the prevalence of noise-induced hearing loss (NIHL) in young adults. NIHL prevalence was found to be substantially higher when hearing thresholds were obtained with supra-aural compared to insert receivers on the same subjects. Real-ear sound pressure levels at 4000, 6000, and 8000 Hz were the major predictors of notched-audiograms obtained with supra-aural headphones. Distortion-product otoacoustic emissions were not significantly different between ears with and without notched-audiograms obtained with supra-aural headphones. The results demonstrated that supra-aural transducer-related artifacts can mimic a notch-like pattern leading to overestimation of NIHL prevalence.
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I. INTRODUCTION

Audiometric calibration is accomplished to deliver known signals to the tympanic membrane (TM) while performing audiological assessment. Accuracy of clinical judgement is critically dependent on audiometric calibration. National and international bodies have laid out standards for audiometric calibration which include standard operating procedures and use of standardized equipment to carry out the calibration process (e.g., IEC 60645-1, 2001; ANSI S3.6-2010, 2010). Traditionally, supra-aural earphones and insert earphones are widely used to measure hearing sensitivity in the conventional frequency range (250–8000 Hz). The supra-aural headphones are commonly calibrated using a 6-cc coupler, whereas the insert earphones are calibrated using a 2-cc coupler (ANSI S3.6-2010, 2010). The supra-aural transducers are calibrated by applying a static force of 4.5 N ($\pm$0.5 N) to simulate tension applied by the headphone band in typical conditions (ANSI S3.6-2010, 2010). The calibrated headphones, regardless of their type, should produce identical real-ear sound pressure levels (RESPLs) at the TM. However, they have been shown to produce variable RESPLs at the TM in real ears (Valenete *et al.*, 1994). Additionally, the supra-aural headphones have been shown to produce high variability in threshold measurement around 6000 Hz (Frank and Vavrek, 1992). High variability in the performance of calibrated supra-aural headphones might be influenced by variability in headband design, head size and headphone placement (Barlow *et al.*, 2014).

High variability in threshold measurements, especially around 6000 Hz, can influence investigation of noise-induced hearing loss (NIHL) in young adults. NIHL is often characterized by the presence of an audiometric notch at 3000, 4000, or 6000 Hz (Kirchner *et al.*, 2012). The audiometric notch is described as reduced hearing thresholds around 3000–6000 Hz compared to the surrounding frequencies. The notch is considered a clinical indication of noise-induced cochlear damage, and it is widely used to investigate the prevalence and risk-factors of NIHL (e.g., Phillips *et al.*, 2010; Niskar *et al.*, 2001; Coles *et al.*, 2000). However, it has been suggested that reduced RESPLs around 6000 Hz resulting from a calibration error can produce notched audiograms in the absence of cochlear damage (Bhatt and Guthrie, 2017; Schlauch and Carney, 2011; Robinson, 1988). The present study investigates the effects of supra-aural and insert headphones on the prevalence of NIHL by (1) comparing the prevalence of the audiometric notch between TDH-50 P and ER-3 A receivers in a sample of young adults, (2) documenting the relation between notch and RESPLs produced by supra-aural and insert headphones, and (3) documenting the relation between audiometric notch and distortion product otoacoustic emissions (DPOAEs) to determine if the notch is associated with cochlear damage.

II. METHODS

A. Subjects

The Institutional Review Board of Northern Arizona University reviewed and approved the study protocol. A sample of 53 healthy adults (18 males and 35 females) aged 18 to 35 years with normal otoscopic and tympanometric findings (static compliance between 0.35 and 1.75 cc and peak pressure value between +50 and −100 daPa) were considered for testing.

B. Hearing thresholds and RESPL measures

All audiometric measures described in this study were collected in a sound treated booth meeting ANSI standards (ANSI S3.1-1999, 1999). Audiometric thresholds were obtained at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz (GSI-61, Eden Prairie, MN) with two transducers: TDH-50 P (Telephonics, Farmingdale, NY) and ER-3 A insert receivers (Etymotic Research, Inc., Elk Grove Village, IL), using the

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modified Hughson-Westlake procedure with a 5 dB step size. TDH-50 P and ER-3 A transducers were calibrated using a standard procedure described by ANSI S3.6-2010 (2010) (see supplementary material[1]). One transducer was selected from the TDH-50P pair, and one was selected from the ER-3A pair to measure the audiometric data for both ears. This was accomplished to limit the influence of calibration error between two sides of the same transducer on the audiometric measures.

RESPL measurement was performed on 24 participants (i.e., 47 ears following the inclusion criteria). RESPLs were measured at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz using RM500 (Audioscan, Ontario, NOL). The probe-microphone system was calibrated with respect to the reference microphone prior to RESPL measurement for each ear. The acoustic method was utilized to place the probe microphone close to the TM to ensure accurate measurement of RESPLs up to 8000 Hz (Dirks *et al.*, 1996). The transducers were placed on the ears without changing the insertion depth of the probe and RESPL values were measured by presenting continuous puretones at 70 dB hearing level (HL) at each audiometric frequency. The threshold difference (ΔThreshold) and RESPL difference (ΔRESPL) at each frequency were calculated.

C. DPOAE measurement

DPOAEs were measured using the SmartDPOAE system (version 5.10, Intelligent Hearing System, Miami, FL) connected to a ER-10D probe (Etymotic Research. Inc, Elk Grove Village, IL). DPOAEs at 2f1-f2 were measured for F_2 values ranging from 1000 to 16 000 Hz in two data points/octave. A stimulus frequency ratio of 1.22 and stimulus–level combinations of 55/40, 65/55, and 75/75 dB sound pressure level (SPL) were used (Poling *et al.*, 2014). A maximum of 64 sweeps were presented until one of the stopping conditions was reached: SNR > 12 dB or a noise floor of < −20 dB SPL. DPOAEs were measured for 45 subjects who agreed to the time commitment necessary to carry out this procedure.

D. Audiometric notch

The audiometric notch was defined using three independent criteria described in the literature: (1) The criteria of Phillips *et al.*: a notch of at least 15 dB or more at 4000 and 6000 Hz followed by recovery of 5 dB in hearing threshold at subsequent high frequency in a linear progression of frequencies (Phillips *et al.*, 2010). (2) The criteria of Niskar *et al.*: thresholds at 500 and 1000 Hz ≤ 15 dB HL, maximum threshold at 3000, 4000, or 6000 Hz ≥ 15 dB above the highest threshold value at 500 and 1000 Hz, and threshold at 8000 Hz ≥ 10 dB lower than the maximum threshold value for 3000, 4000, or 6000 Hz (Niskar *et al.*, 2001). (3) The criteria of Coles *et al.*: Threshold worse by ≥10 dB at 3, 4, or 6 kHz than those at 1 or 2 kHz and 6 or 8 kHz (Coles *et al.*, 2000). Each ear was classified into two groups using these criteria: ears with no notch and notch.

III. RESULTS

A. Comparison of hearing thresholds and RESPLs obtained with TDH-50 P and ER-3 A receivers

Average hearing thresholds obtained using ER-3 A receiver were significantly different ($p < 0.0001$) than the average hearing thresholds obtained using TDH-50 P receiver for the audiometric frequencies at 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz [Fig. 1(a)]. Similarly, average RESPLs obtained using the ER-3 A receiver were significantly different ($p < 0.0001$) than average RESPLs obtained using TDH-50 P receiver for audiometric frequencies at 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz [Fig. 1(b)].

B. Relation between hearing thresholds and RESPLs obtained with TDH-50 P and ER-3 A receivers

Figure 2 shows ΔRESPL as a function of ΔThreshold at each audiometric frequency. The correlation coefficients between ΔRESPL and ΔThreshold was statistically significant ($p < 0.05$) at each frequency. The strongest correlation coefficient was obtained at 6000 Hz ($r = -0.879$, $p < 10^{-15}$) followed by 8000 Hz ($r = -0.754$, $p < 10^{-9}$).

C. Prevalence of the audiometric notch between ER-3 A and TDH-50 P receivers

The prevalence of a notched audiogram was 3%, 10%, and 0% for the criteria of Phillips *et al.* (2010), Coles *et al.* (2000), and Niskar *et al.* (1998), respectively, when the ER-3 A receiver was used to measure the hearing thresholds. The prevalence raised to 30%, 26%, and 12% for the criteria of Phillips *et al.* (2010), Coles *et al.* (2000), and Niskar *et al.* (1998), respectively, when the TDH-50 P receiver was used to measure the hearing thresholds. The McNemar's analyses showed that the differences in the prevalence of notches identified using the criteria of Phillips *et al.* (2010) and Coles *et al.* (2000) between the transducers were statistically

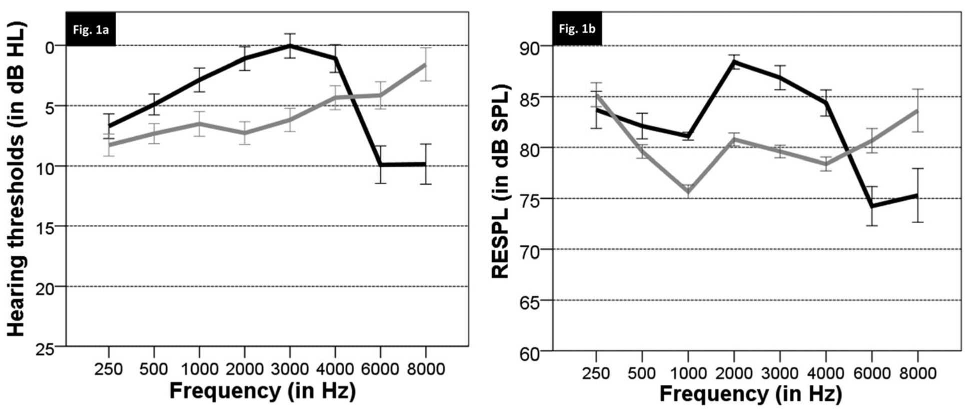

FIG. 1. Results of the audiometric measurements are presented. (a) and (b) present hearing thresholds (in dB HL) and RESPLs (in dB SPL) obtained with ER-3 A and TDH-50 P receivers as a function of the audiometric frequencies, respectively. Error bars indicate 95% confidence interval.

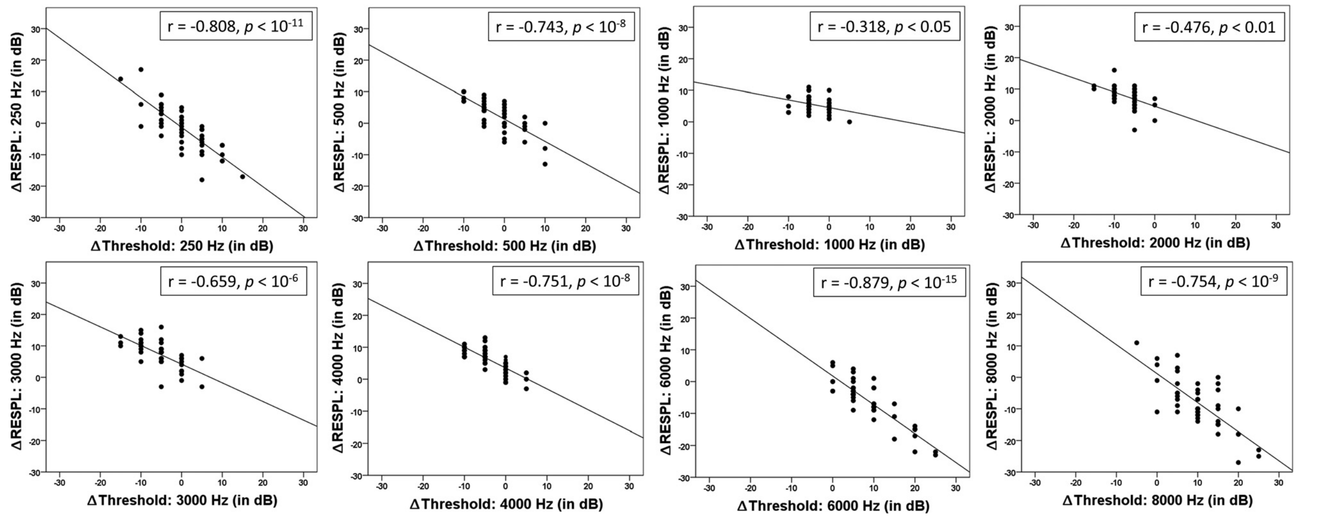

FIG. 2. Scatter plots between ΔRESPL and ΔThreshold are shown at each audiometric frequency. A linear regression line, Pearson's correlation coefficient (r) and *p* value are presented. ΔThreshold was calculated by subtracting hearing threshold obtained by ER-3 A receiver from hearing threshold obtained by TDH-50 P receiver at each frequency. ΔRESPL was calculated by subtracting RESPL obtained by ER-3 A receiver from RESPL obtained by TDH-50 P receiver at each frequency.

significant [$p < 10^{-6}$ for the criteria of Phillips *et al.* (2010) and $p < 0.002$ for Coles *et al.* (2000)]. McNemar's statistics could not be obtained for the criteria of Niskar *et al.* (1998) as the prevalence of a notched audiogram was found to be 0% with ER-3 A receiver. Subjects with notched audiograms exhibited on an average shorter length of the ear canal compared to subjects with no notched audiogram obtained with TDH-50 P receiver ($MD = 0.13$ in.).

D. Relation between RESPLs and notched audiograms

Binary logistic regression analyses were performed to list predictors for the notched audiograms. For the criteria of Phillips *et al.* (2010), RESPL at 6000 Hz [odds ratio (OR): 0.612 (95% CI: 0.457–0.820), $p = 0.001$] and 8000 Hz [OR: 1.247 (95% CI: 1.032–1.506), $p = 0.02$] showed significant association with the prevalence of notched audiograms (Cox and Snell $R^2 = 0.53$). For the criteria of Coles *et al.* (2000), RESPL at 4000 Hz [OR: 1.716 (95% CI: 1.013–2.906), $p = 0.045$], 6000 Hz [OR: 0.538 (95% CI: 0.353–0.820), $p = 0.004$], and 8000 Hz [OR: 1.374 (95% CI: 1.041–1.813), $p = 0.025$] showed significant association with the notched audiogram (Cox and Snell $R^2 = 0.54$). Similarly, a binary logistic regression analysis using the criteria of Niskar *et al.* (1998) with two dependent variables, RESPL at 6000 and 8000 Hz, revealed that RESPL at 6000 Hz [OR: 0.727 (95% CI: 0.589–0.896), $p = 0.003$] demonstrated significant association with the notched audiogram (Cox and Snell $R^2 = 0.33$). The number of notched audiograms for hearing thresholds obtained using ER-3 A receiver with the criteria of Phillips *et al.* (2010), Coles *et al.* (2000), and Niskar *et al.* (1998) were 2/47, 3/47, and 0/47, respectively. Therefore, the regression analysis could not be performed on these data.

E. Relation between notched audiograms and DPOAEs

Repeated measure analyses of variance (ANOVAs) were performed to determine the relation between DPOAEs and notched audiograms at three stimulus levels, 55/40, 65/55, and 75/75 dB SPL. DPOAEs showed no significant relation ($p > 0.05$) to notched audiograms identified using any notch identification criteria when hearing thresholds were measured using the TDH-50 P headphone (see supplementary material[1]). The number of notched audiograms for hearing thresholds obtained using ER-3 A receiver with the criteria of Phillips *et al.* (2010), Coles *et al.* (2000), and Niskar *et al.* (1998) were 2/47, 3/47, and 0/47, respectively. Therefore, the repeated measure ANOVAs could not be performed on these data.

IV. DISCUSSION

The major findings of the study are (1) the prevalence of notched audiograms was substantially higher when TDH-50 P receivers were used to measure hearing thresholds compared to ER-3 A receivers, (2) RESPLs at 4000, 6000, and 8000 Hz were the major predictors of notched audiograms when TDH-50 P receivers were used to measure hearing thresholds, and (3) individuals with a notched audiogram measured with TDH-50 P receivers did not show convincing evidence of cochlear dysfunction as assessed by DPOAEs. The results showed that the outer ear resonance characteristics can mimic a notch-like pattern in the audiogram when supra-aural receivers were used to measure hearing thresholds. The notch disappeared in most subjects when ER-3 A receivers were used to measure hearing thresholds. The results of the study are in agreement with a previously published report showing that RESPL values of TDH-style and insert receivers are substantially different (Valenete *et al.*, 1994), and can influence hearing threshold measurement at high frequencies (Lawton, 2005). Therefore, the supra-aural receivers should not be used to investigate NIHL in young adults especially when less restrictive notch identification criteria are utilized to identify NIHL.

A. Audiometric notch and standing waves in the ear canal

Cochlear hair cells are one of the most vulnerable structures to noise-induced damage (e.g., Chen and Rechter, 2003).

DPOAEs are generally considered more sensitive in identifying noise-induced cochlear damage compared to behavioral hearing thresholds (Attias *et al.*, 2001). The present study showed no group difference between subjects with and without an audiometric notch using TDH-50 P receivers in DPOAE measurements. Instead, the study found that subjects with notched audiograms exhibited shorter ear canal length compared to subjects with no notched audiogram. Hearing threshold measurements, especially around 6000 Hz, are likely to be influenced by standing waves in the ear canal in subjects with shorter ear canal length (Dirks *et al.*, 1996; Lawton, 2005). Overall, the results demonstrated that subjects can exhibit notched audiograms without noise-induced cochlear damage when TDH style receivers are used.

B. Overestimation of NIHL in young adults and strategies to reduce false-positives

Major epidemiological investigations of NIHL, including National Health and Nutrition Examination Survey (1988–2018), have utilized supra-aural headphones (e.g., Bhatt and Guthrie, 2017; Mahboubi *et al.*, 2013; Henderson *et al.*, 2011; Shargorodsky *et al.*, 2010; Agarwal *et al.*, 2016; Niskar *et al.*, 2001). These studies have reported higher prevalence of NIHL in young adults compared to a study utilizing insert receivers for hearing threshold measurements (Le Prell *et al.*, 2011). The present study showed that insert receivers with low impedance values (e.g., ER-3 A, 50 Ω) should be preferred over supra-aural headphones when investigating NIHL in young adults. Another possible way to improve hearing threshold measurement is by using real ear calibration procedures such as the depth-compensated simulator (Lee *et al.*, 2012) or forward pressure level (Scheperle *et al.*, 2008). These methods are least influenced by standing waves in the ear canal and have been shown to produce less variable hearing thresholds at high frequencies (Souza *et al.*, 2014).

V. CONCLUSIONS

The prevalence of NIHL is influenced by supra-aural transducer-related artifact. It was concluded that the supra-aural receivers should not be used to estimate the prevalence of NIHL in young adults especially when less restrictive notch identification criteria are used.

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[1]See supplementary material at https://doi.org/10.1121/1.5030924 for results of the calibration procedure for TDH-50 P and ER-3 A and results of DPOAEs between subjects with and without audiometric notch.

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