Determinants of the Audiometric Notch at 4000 and 6000 Hz in Young Adults

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J Am Acad Audiol 2020;31:371–383.

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Abstract

Background Noise-induced hearing loss (NIHL) is often characterized by the presence of an audiometric notch at 3000-6000 Hz in a behavioral audiogram. The audiometric notch is widely used to investigate NIHL in children and young adults. However, the determinants of the audiometric notch in young adults largely remain unknown.

Purpose The study aimed to investigate the determinants of the audiometric notch in young adults.

Research Design A cross-sectional design was adopted for the study.

Study Sample A sample of 124 adults (38 males and 86 females) aged 18-35 years with normal otoscopic and tympanometric findings was recruited.

Data Collection and Analysis Hearing thresholds and real-ear sound pressure levels (RESPLs) were obtained with calibrated ER-3A (Etymotic Research, Elk Grove Village, IL) andTDH-50P receivers (Telephonics, Farmingdale, NY). Distortion-product otoacoustic emissions (DPOAEs) were used to evaluate the cochlear function. The external auditory canal (EAC) length was measured using the acoustical method. Noise exposure background (NEB) was estimated using the Noise Exposure Questionnaire. The notched audiograms were identified using: Phillips, Coles, and Niskar criteria.

Results The prevalence of notched audiograms was substantially higher for TDH-50P supra-aural receivers than for ER-3A insert receivers. RESPLs at 6000 and 8000 Hz were the major predictors of notched audiograms for TDH-50P receivers. These predictors explained around 45% of the variance in the notched audiograms. The notched audiograms obtained with TDH-50P receivers showed no association with NEB. Individuals with notched audiograms measured using TDH-50P did not show convincing evidence of cochlear dysfunction as assessed by DPOAEs. Individuals with notched audiograms obtained with TDH-50P receivers revealed an average of shorter EAC and a poorer hearing threshold at 6000 Hz.

Conclusions The calibration error in the RESPLs at 6000 and 8000 Hz that are likely to be influenced by the shorter EAC was the major determinant of the notched audiograms when the supra-aural transducers were used to measure hearing thresholds. Therefore, the supra-aural receivers should not be used to estimate the prevalence of NIHL in children and young adults when the less restrictive notch identification criteria are used to identify NIHL. Real-ear calibration techniques that are least influenced by the standing waves in the EAC should be preferred when investigating the prevalence of and risk factors for NIHL in young adults.

Keywords
- audiometric notch
- noise-induced hearing loss
- notched audiograms
- real-ear sound pressure level
- real-ear threshold sound pressure level

DOI https://doi.org/10.3766/jaaa.19030.
ISSN 1050-0545.

Introduction

Noise-induced hearing loss (NIHL) remains a major hearing health concern despite the Occupational Safety and Health Administration implementing standards for hearing protection and public health awareness campaigns. According to recent reports, NIHL affects approximately 15% of US adults aged 20-69 years, and it is a frequently occurring disability among current combat veterans (NIDCD[26]). Recent investigations suggest that NIHL is no longer limited to industrial workers exposed to loud noise, but it is also documented in adolescents, young adults, and college-aged musicians (Phillips et al[43]; Henderson et al[18]; Bhatt and Guthrie[6]).

Cochlear hair cells are one of the most vulnerable structures to noise-induced damage. Noise-induced hair cell damage can cause a reduction in hearing sensitivity at frequencies around 3000 to 6000 Hz (Cody and Russell[12]; Subramaniam et al[57]; Chen and Fechter[11]). NIHL is often characterized by the presence of an audiometric notch at 3000, 4000, or 6000 Hz (Kirchner et al[20]). The audiometric notch is widely used to report NIHL prevalence despite its variable operational definitions (e.g., Coles et al[13]; Niskar et al[38]; Phillips et al[43]; Carter et al[9]). The notch identification criteria have a significant influence on the reported prevalence of NIHL. The prevalence of NIHL varies greatly, from 11.7% to 47.2%, depending on which notch identification criteria are used (Nondahl et al[40]).

The determinants of the audiometric notch in young adults remain largely unknown. Despite the widespread utility of the audiometric notch in investigating the epidemiology of NIHL (e.g., Carter et al[9]; Wei et al[61]), a relationship between noise exposure and the audiometric notch remains elusive (e.g., McBride and Williams[31]; Lie et al[27]). One possible reason might be the audiometric calibration-related factors that might influence the notch identification process. National and international bodies have laid out standards for audiometric calibration that include standard operating procedures and the use of standardized equipment to carry out the calibration process (e.g., IEC 60645-1[19]; ANSI S3.6[2]). 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[2]). The supra-aural transducers are calibrated by applying a static force of 4.5 N (6 0.5 N) to simulate tension applied by the headphone band under typical conditions (ANSI S3.6[2]). The calibrated headphones, regardless of their type, should produce identical real-ear sound pressure levels (RESPLs) at the tympanic membrane (TM). However, they have been shown to produce variable RESPLs at the TM in real ears (Valente et al[59]).

In addition, the supra-aural headphones have been shown to produce high variability in threshold measurement around 6000 Hz (Frank and Vavrek[17]). High variability in the performance of calibrated supra-aural headphones around 6000 Hz might be influenced by variability in headband design, head size, and headphone placement (Barlow et al[4]). High variability in the performance of supra-aural headphones is a major concern because epidemiological studies have revealed that a high percentage of audiometric notches appear at 6000 Hz for children and young adults when supra-aural headphones are used to measure hearing thresholds (e.g., Niskar et al[38]; Phillips et al[43]; Carter et al[9]). Elevation of the hearing threshold at 6000 Hz and the subsequent appearance of a notch can be influenced by an error in the calibration reference value rather than by noise-induced cochlear damage (e.g., Schlauch and Carney[47]; Schlauch and Carney[48]; Bhatt and Gurthrie[6]).

►**Table 1** presents a summary of the commonly used notch identification criteria, transducer type, and their influence on the prevalence of NIHL. ►**Table 1** suggests that studies using supra-aural receivers reported a higher prevalence of notches than the one which used insert receivers (Le Prell et al[23]). Using the supraaural receivers, the overall prevalence of notched audiograms was around 45% in student musicians (Phillips et al[43]) and around 56% in non-institution-alized US adolescents and young adults (Bhatt and Guthrie[6]). The notch prevalence was estimated to be around 12.5–16.3% for children and young adults using relativ ely stringent notch identification criteria (Niskar et al[38]; Henderson et al[18]). The prevalence of notched audiograms was estimated to be 0% when ER-3A insert receivers were used to measure hearing thresholds (Le Prell et al[23]). About 7% of the particip ants showed a notched audiogram when notch identification was performed using less stringent notch identification criteria.

The present study hypothesized that (a) the prevalence of notched audiograms would be higher when hearing thresholds are measured using TDH receivers than when using insert receivers, and (b) the calibration error in RESPLs resulting from individual variation in outer-ear resonance would predict the presence of notched audiograms. The second hypothesis implies that individuals with notched audiograms will not exhibit noise-induced cochlear damage and substantial history of noise exposure in daily life if the notched audiograms are produced because of calibration error in the RESPL. Therefore, the firs t goal of the present study was to compare the prevalence of notched audiograms in a sample of young adults between two transducer types: TDH-50P, and ER-3A receivers. The study used three notch identification criteria to identify NIHL: (a) Phillips' (Phillips et al[43]), (b) Coles' (Coles et al[13]), and (c) Niskar's (Niskar et al[38]). These criteria have been widely used to estimate NIHL in young adults (e.g., Niskar et al[39]; Niskar et al[38]; Nondahl et al[40]; Phillips et al[43]; Shargorodsky et al[50]; Shargorodsky et al[51]; Le Prell et al[23]; Lee et al[24]; Lie et al[27]; Phillips et al[44]; Bhatt and Guthrie[6]). The second goal was to investigate the relation among notched audiograms, RESPLs, length of the external auditory canal (EAC), and noise exposure background (NEB) for supra-aural and insert receivers. NEB was defined as the amount of noise exposure an individual has encountered in daily life. The third goal was to investigate the relation between notched audiograms and distortion-product otoacoustic emissions (DPOAEs) to determine if the notch audiograms are associated with cochlear damage.

Table 1 A Brief Summary of Research Highlighting the Notch Criteria and Transducer Type Used in Previous Research

Study	Notch Identification Criteria	Transducer	Population	Findings
Niskar et al (2001)[38]	(1) 500 and 1000 Hz thresholds ≤15 dB HL; (2) threshold worse by ≥ 15 dB at 3000, 4000, or 6000 Hz than the thresholds at 500 and 1000 Hz; and (3) 8000 Hz threshold ≥10 dB than the worse threshold at 3000, 4000, or 6000 Hz	TDH-39P	NHANES (1988-1994), age: 6-19 years (N = 6,166)	Overall: 12.5%
Henderson et al (2011)[18]	Niskar et al (2001)[38]	TDH-39P	NHANES (1988-1994; 2005–2006), age: 12-19 years (N = 6,166)	Overall: 16.35%
Phillips et al (2010)[43]	ND = PT − BT, where (1) ND is the notch depth ≥15 dB, (2) PT is the poorest threshold at 4000 and 6000 Hz followed by recovery of 5 dB in the hearing threshold at subsequent high frequency, and (3) BT is the best threshold at 4000, 3000, 2000, or 1000 Hz in a linear progression of frequencies	TDH-50P	Music students aged 18-25 years (N = 329)	Overall: 45%
Bhatt and Guthrie (2017)[6]	Phillips et al (2010)[43]	TDH-39P	NHANES (2005-2010), age: 12-19 years (N = 2,348)	Overall: 55.6%
Nondahl et al (2009)[40]	Multiple notch identification criteria were used. One of which was proposed by Coles et al (2000)[13]: (1) threshold worse by ≥ 10 dB at 3, 4, or 6 kHz than those at 1 or 2 kHz and 6 or 8 kHz	THD-50P	Epidemiology of Hearing Loss Study, age: 43-84 years (N = 3,753)	Overall: 31.7
Le Prell et al (2011)[23]	Two notch identification criteria were used: (1) Niskar et al (2001)[38] and (2) Coles et al (2000)[13]	ER-3A	College-aged students with self-reported normal hearing (N = 57)	Niskar's criteria, overall: 0% Coles' criteria, overall: 7%

Methods

Ethics Statement

The Institutional Review Board of Northern Arizona University reviewed and approved the study protocol. Participants were recruited from students enrolled at the Flagstaff Mountain campus of Northern Arizona University. A written informed consent was obtained for each participant before the data collection process.

Participants

A recruitment flyer was distributed among university classes at the Flagstaff campus of Northern Arizona University. The students were instructed to contact the investigator to participate in the study. A sample of 145 adults (55 males and 90 females) aged 18-35 years was recruited. An otoscopic examination was performed on all participants. Tympanometry was performed using a 226 Hz probe tone presented through Titan IMP440 (Interacoustics, Middelfart, Denmark) on participants with normal otoscopic findings. Participants with normal tympanograms (static compliance between 0.35 and 1.75 cc and peak pressure value between +50 and -100 daPa) were considered for further testing. Along with otoscopy and tympanometry, an informal interview was conducted to rule out active middle-ear pathologies. Participants reporting systemic diseases and neurological or immunological disorders were excluded from the study. Data from 247 ears from 124 participants (38 males and 86 females) m et the inclusion criteria. These participants ($N_{Total\_participants} = 124$; $N_{Totai\_ears} = 247$) received further testing.

Audiometric Measures

All audiometric measures described in this study were collected in a sound-treated booth meeting the ANSI standards (ANSI S3.1-1999). Audiometric thresholds were obtained for both ears at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz (GSI-61, Eden Prairie, MN) with two transducers: TDH-50P (impedance = 60 Ω) (Telephonics, Farmingdale, NY) and ER-3A insert receivers (impedance = 50 Ω) (Etymotic Research, Inc., Elk Grove Village, IL), using the modified Hughson-Westlake procedure with a 5-dB step size. Both the TDH-50P and ER-3A transducers were calibrated using a standard procedure described by ANSI S3.6.[2] The audiometric output was adjusted to achieve the closest approximation to target levels at each audiometric frequency. One transducer from the TDH-50P pair and one from the ER-3A pair were selected to measure the audiometric data from both ears for the entire study sample to limit the influence of calibration error between two sides of the same transducer set on the audiometric measures. ►**Figure 1** shows the results of the calibration procedure.

RESPL Measures

EAC length measurement was performed on 38 participants (70 of 76 ears following the inclusion criteria; $N_{EAClength\_ears} = 70$; $N_{EAClength\_participants} = 38$) who agreed to the time commitment necessary to carry out this procedure.

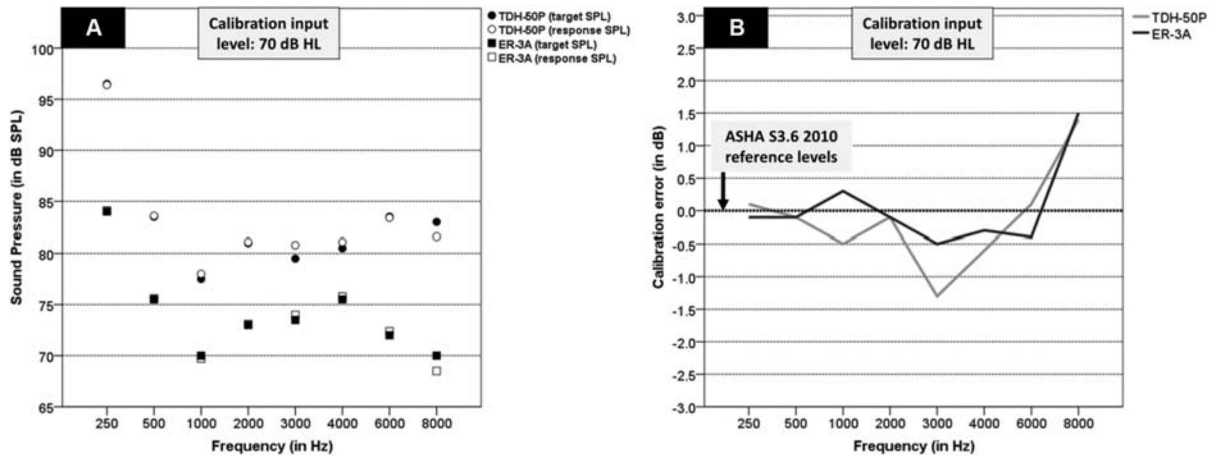

Fig. 1 Results of the calibration procedure. (A) presents the sound pressure level (in dB SPL) generated by ER-3A in a DBO138 2-cc couple (gray line) and sound pressure level (in dB SPL) generated by TDH-50P receivers (black line) in a Bruël and Kjaer artificial ear (IEC 60318-1 coupler) as a function of the audiometric frequencies. (B) presents calibration error (in dB) for TDH-50P and ER-3A receivers as a function of the audiometric frequencies. The calibration error was calculated by the subtracting response SPL value from the target SPL value at each audiometric frequency. The dashed line represents the normalized sound pressure level (ANSI S3.6[2]). Note that the differences in the calibration error across the frequency range for both the transducers did not exceed 1.5 dB at any frequency.

Among these 38 participants, complete RESPL measurement was taken on 33 participants (64 ears meeting the inclusion criteria; $N_{RESPL\_ears} = 64$; $N_{RESPL\_participants} = 33$). RESPLs were measured at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz using RM500 (Audioscan, Ontario, Canada, NOL). RM 500 has a probe microphone assembly containing two microphones; a silicone probe microphone was used to measure the RESPL in the EAC, and a second microphone located close to the pinna ofthe test ear was used as a reference microphone. The probe microphone system was calibrated to the reference microphone before RESPL measurement for each ear. The acoustic method was used to place the probe microphone close to the TM because it has been shown to produce a better RESPL measurement (Dirks et al[14]). This method takes the quarter-wave antiresonance property of the outer ear into account when determining the location of the probe microphone relative to the TM. The initial measurements from the probe microphone were used to identify the frequency of the first standing wave minimum occurring in the real-ear unoccluded response curve. The probe microphone was inserted in the EAC while observing the minimum in the frequency spectrum moving toward 8000 Hz and was placed in the EAC at the place where the minimum was not observed at frequencies ≤8000 Hz. It was marked to indicate the insertion depth with reference to the intratragus notch and was taped to the pinna to ensure placement accuracy between measurements. The marking on the probe microphone was used to measure the length of the EAC. TDH-50P headphones were placed on the ears, and RESPL values were measured by presenting continuous puretones at 70 dB HL at each audiometric frequency. Hearing thresholds were measured using the modified Hughson-Westlake procedure with a 5-dB step size without changing the placement of the headphones.

The real-ear unoccluded response curve was measured again to ensure that the probe placement did not change while conducting the RESPL and hearing threshold measurements for TDH-50P headphones. The ER-3A receiver with a foam eartip was inserted in the EAC without changing the insertion depth of the probe microphone. RESPL values were measured at each audiometric frequency with continuous pure-tones presented at 70 dB HL through the ER-3A receiver. Hearing thresholds were measured using the modified Hughson-Westlake procedure with a 5-dB step size. The threshold difference (ΔThreshold) was calculated by subtracting the hearing threshold value obtained with the ER-3A receiver from that obtained with the TDH-50P receiver at each frequency. The RESPL difference (ΔRESPL) at each frequency was calculated by subtracting the RESPL value obtained with the ER-3A receiver from the RESPL value obtained with the TDH-50P receiver at each frequency.

The RESPL was used to estimate the real-ear threshold sound pressure level (RETSPL) because (a) the RETSPL measurement may not be possible to obtain because of the noise floor (typically around 40 dB SPL) of the probe-tube microphone (Munro and Davis[33]), and (b) the RESPL measured using 70 dB HL stimuli would exhibit a linear relationship with the stimulus intensity because of the calibrated attenuator linearity (ANSI 3.6[2]). Therefore, the RESPL measurement was used to estimate RETSPL for audiometric headphones in the previous investigations (Scollie et al[49]; Munro and Lazenby[34]).

DPOAE Measurement

DPOAEs were measured using the SmartDPOAE system (version 5.10, Intelligent Hearing System, Miami, FL) connected to the ER-10D probe (Etymotic Research, Inc). The DPOAE probe was calibrated in an IEC-711 ear simulator before data collection. The in-ear probe calibration test, as recommended by SmartDPOAE software, was performed before collecting DPOAEs. F_2 values ranging from 1000 to 16000 Hz at two data points/octave were used for DPOAE measurement. A stimulus frequency ratio of 1.22 and stimulus level combinations of 55/40, 65/55, and 75/75 dB SPL were used (Kummer et al[21]; Poling et al[45]). A maximum of 64 sweeps was presented until one of the stopping conditions was reached: SNR >12 dB or a noise floor of <-20 dB SPL. DPOAEs were measured for 87 participants (170 of 174 ears following the inclusion criteria; $N_{DPOAE\_ears} = 170$; $N_{DPOAE\_participants} = 87$) who agreed to the time commitment necessary to carry out this procedure.

Questionnaire

A questionnaire was constructed to investigate demographic details, medical and audiological history, and NEB (see Supplemental Appendix S1, supplemental to the online version of this article): (a) demographic details: Participants were asked about their age, gender, and ethnicity. (b) Medical and audiological history: The question about medical history was "What illnesses do you have or have you had? Please check all that apply." Response choices included meningitis, high blood pressure, head injury, diabetes, mumps, heart trouble, malaria, scarlet fever, and others. The questions about audiological history asked about hearing loss and middle-ear infection. These questions read "Do you have hearing loss?" and "Do you have a history of ear infection?" Response choices included yes, no, and do not know. Participants with no medical and audiological history were included in the statistical analysis. (c) NEB: NEB was estimated via a self-report questionnaire developed by Megerson et al.[32] NEB was defined as the amount of noise exposure an individual has encountered in daily life. The survey was validated to estimate overall acoustic exposure (Megerson et al[32]). It was used in previous research to quantify noise exposure in young adults (Stamper and Johnson[54]; Bhatt[5]). It assessed nine specific known areas of high acoustic exposure. These included exposure to six areas of noise exposure: occupational noise, power tools, heavy equipment, commercial sporting or entertainment events, motorized vehicles, and small aircraft; and three areas of music exposure: music instrument playing, music listening via personal earphones, and music listening via audio speakers. The survey included questions about frequency (i.e., how often) and duration (i.e., how long) of noise exposures. The responses were elicited using a forced choice method. Responses were rated categorically to calculate the overall noise exposure which was reported as $L_{Aeq8760h}$. Here, "*L*" represents the sound pressure level measured in dB, "*A*" represents the use of an A-weighted frequency response, "eq" represents a 3-dB exchange rate for calculation of the time/level relationship, and "8760 h" represents the total duration of noise exposure in hours over 1 year (365 days/year $\times$ 24 hours/day). Music exposure was calculated by cumulating the noise dose for the three areas of music exposure listed earlier. Further details on the survey can be found in Megerson et al[32] and Stamper and Johnson.[54] Complete survey data were received from 95 participants ($N_{survey\_participants} = 95$).

Audiometric Notch

The audiometric notch was defined using three independent criteria described in the literature: (a) Phillips' criteria used a formula: ND = PT − BT, where ND is a notch depth of at least 15 dB or more, PT is the poorest threshold at 4000 and 6000 Hz followed by recovery of 5 dB in the hearing threshold at subsequent high frequency, and BT is the best threshold at 4000, 3000, 2000, or 1000 Hz in a linear progression of frequencies (Phillips et al[43]); (b) Niskar's criteria: thresholds at 500 and 1000 Hz $\leq$ 15 dB HL, maximum threshold at or 6000 Hz $\geq$ 15 dB above the highest threshold value at 500 and 1000 Hz, and threshold at 8000 Hz $\geq$ 10 dB lower than the maximum threshold value for or 6000 Hz (Niskar et al[38]); (c) Coles' criteria: threshold worse by $\geq$10 dB at 3, 4, or 6 kHz than those at 1 or 2 kHz and 6 or 8 kHz (Coles et al[13]). Each ear was classified into two groups using these criteria: the ear with no notch and with a notch.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics 23.0 for Windows (IBM Software Group, Chicago, IL). The right and left ear data were collapsed to compare the prevalence of notched audiograms between the transducers and to investigate the influence of RESPLs on notched audiograms, RESPLs, and length of EAC. It was reasoned that the calibration error in RESPLs is dependent on the morphological variations of the outer ear. There is evidence indicating morphological asymmetry between right and left ears (Verma et al[60]). Therefore, the data from the right and left ears were treated independently to test the study hypotheses.

The prevalence of no notch and notch was calculated within the study sample ($N_{Total\_ears} = 247$). Paired sample t-tests with Bonferroni correction were performed to test if hearing thresholds and RESPLs were significantly different between the transducers. The McNemar's test was performed to determine the difference in the prevalence of notches between the transducers. A binary logistic regression analysis was performed with a dichotomous dependent variable (i.e., presence or absence of the audiometric notch) and with eight independent variables (i.e., RESPLs at each audiometric frequency) to determine the relationship between the notch and RESPLs ($N_{RESPL\_ears} = 64$). The regression analyses were performed using an "enter" method, and a p-value $\leq$0.05 was considered the threshold for statistical significance. Repeated measure analysis of variances (ANOVAs) with nine within-subject factors (i.e., DPOAE amplitudes at each test frequency) and one between-subject factor (i.e., the presence or absence of the audiometric notch) were performed to determine the relation between DPOAEs and the notch ($N_{DPOAE_ears} = 170$). One-way ANOVA was used to examine the relationship between hearing thresholds and NEB score ($N_{survey_participants} = 95$). Independent sample t-tests were performed to determine the relation between notched audiograms and EAC length ($N_{EAClength_ears} = 70$).

Results

►**Figure 1** presents the results of the calibration process, as described by ANSI S3.6.[2] The audiometric output was adjusted to achieve sound pressure levels in the couplers to approximate the target levels. The calibration error at each audiometric frequency is within the tolerance limit ($\pm$3 dB). The difference in calibration error across the frequency range for both transducers was minimum and did not exceed 1.5 dB at any frequency.

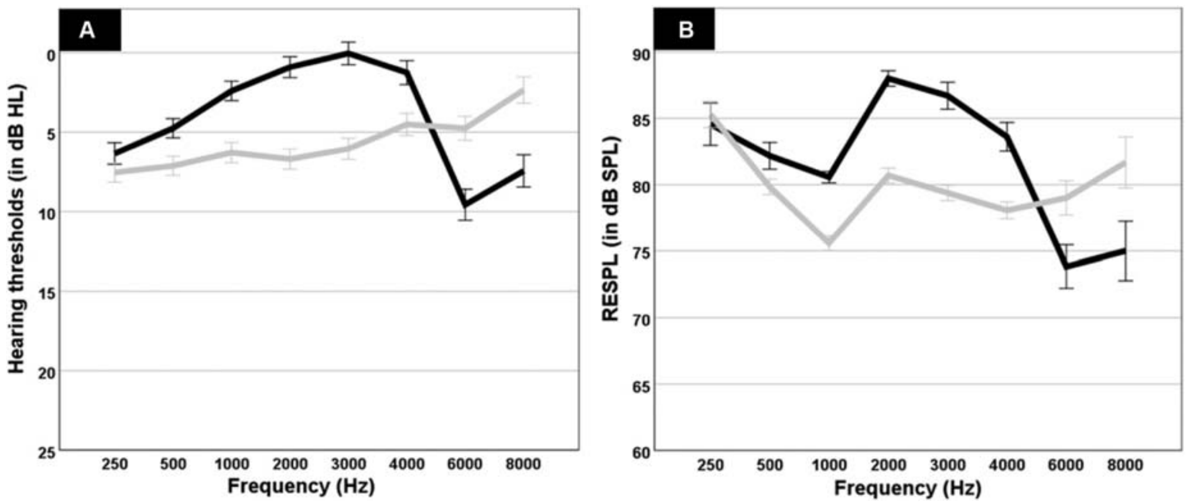

Fig. 2 Results of the audiometric measurements. (A) presents hearing thresholds (in dB HL) obtained with ER-3A (gray line) and TDH-50P (black line) receivers as a function of the audiometric frequencies. Error bars indicate 95% CI. (B) presents the RESPL measured by the probe microphone close to the TM as a function of the audiometric frequencies. Error bars indicate 95% CI.

Comparison of Hearing Thresholds Obtained with TDH-50P and ER-3A Receivers

►**Figure 2A** presents hearing thresholds obtained with TDH-50P and ER-3A receivers at each audiometric frequency on the study sample ($N_{Total\_ears} = 247$). As shown in ►**Figure 2A**, the average hearing thresholds obtained using ER-3A receivers were poorer than the average hearing thresholds obtained using TDH-50P receivers for the audiometric frequencies at 250, 500, 1000, 2000, 3000, and 4000 Hz. The average hearing thresholds obtained using ER-3A were better than those obtained using TDH-50P receivers at 6000 and 8000 Hz. The paired sample *t*-tests with Bonferroni correction ($p = 0.05/8 = 0.00625$) revealed that mean differences were statistically significant at all audiometric frequencies.

Comparison of RESPLs Obtained from TDH-50P and ER-3A Receivers

►**Figure 2B** presents descriptive statistics for RESPLs obtained from ER-3A and TDH-50P receivers at each audiometric frequency ($N_{RESPL\_ears} = 64$). As shown in ►**Figure 2B**, the average RESPLs obtained using ER-3A receivers were higher than average RESPLs obtained using TDH-50P receivers for audiometric frequencies at 500, 1000, 2000, 3000, and 4000 Hz. Average RESPLs for EA-3A were lower than those for TDH-50P at 250, 6000, and 8000 Hz. The paired sample t-tests with Bonferroni correction ($p = 0.05/8 = 0.00625$) revealed that mean differences were statistically significant at 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz.

Relation between Hearing Thresholds and RESPLs Obtained with TDH-50P and ER-3A Receivers

►**Figure 3** presents Pearson's product-moment correlation coefficients ($N_{RESPL\_ears} = 64$) between hearing thresholds and RESPLs obtained with ER-3A and TDH-50P receivers at each audiometric frequency. ►**Figure 3** shows ARESPL as a function of ΔThreshold at each audiometric frequency. The correlation coefficients between ΔRESPL and ΔThreshold were statistically significant ($p < 0.05$) at each frequency. The strongest correlation coefficients were obtained at 6000 Hz ($r = -0.879$, $p < 10^{-15}$) followed by 8000 Hz($r = -0.754, p < 10^{-9}$). The analysis revealed that a substantial proportion ofvariability in ΔThreshold could be explained by ΔRESPL at each audiometric frequency.

Prevalence of the Audiometric Notch between ER-3A and TDH-50P Receivers

►**Figure 4** presents the prevalence of a notched audiogram in the study sample ($N_{Total\_ears} = 247$). The prevalence of the notch was almost 34% when Phillips's notch identification criteria were used along with TDH-50P receivers. The prevalence reduced to 4.9% when ER-3A receivers were used to obtain the hearing thresholds. The McNemar's test showed that the difference in the prevalence of notches between the transducers was statistically significant ($p < 10^{-16}$). Using Coles' definition, the prevalence of a notched audiogram was obtained to be around 26% when hearing thresholds were obtained with TDH-50P receivers. The prevalence was reduced to 10% when hearing thresholds were obtained with ER-3A receivers. McNemar's test showed that the difference in the prevalence of notches between the transducers was statistically significant ($p < 10^{-6}$). A similar pattern was observed for Niskar's definition where the prevalence of the notched audiogram was 19% with TDH-50P receivers and was reduced to 2% with ER-3A receivers. McNemar's test showed that the difference in the prevalence of notches between the transducers was statistically significant ($p < 10^{-10}$).

Relation between RESPLs and Notched Audiograms

A binary logistic regression analysis ($N_{RESPL\_ears} = 64$) was performed to list predictors for the notched audiograms identified using Phillips' criteria for hearing thresholds obtained with TDH-50P receivers. The analysis revealed that the RESPL at 6000 Hz {odds ratio [OR]: 0.674 (95% confidence interval [CI]: 0.553 - 0.820), $p < 0.0001$} and 8000 Hz (OR: 1.264 [95% CI: 1.093-1.461], $p = 0.002$) showed significant association with the prevalence of notched audiograms. RESPLs at 6000

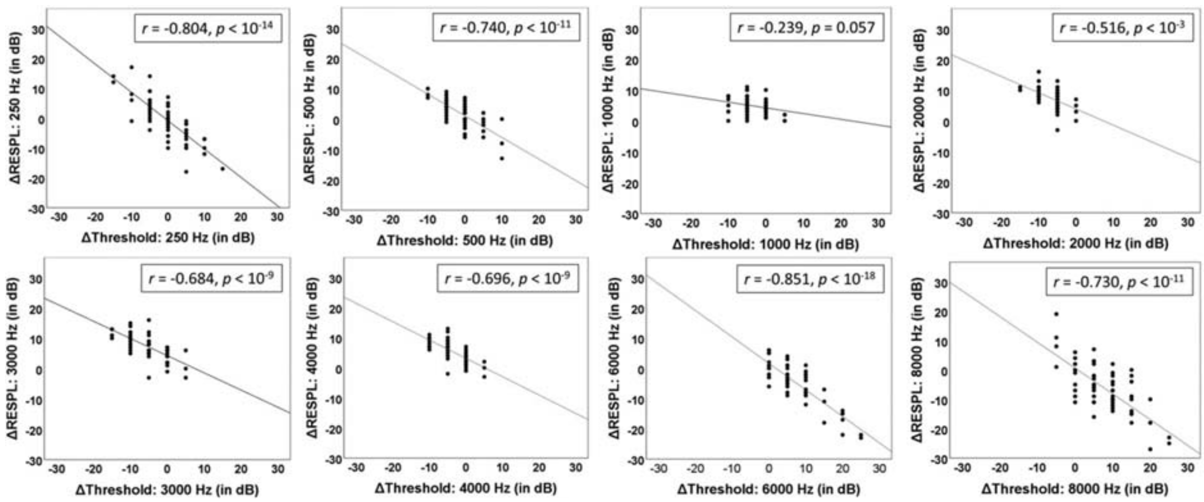

Fig. 3 Scatter plots between ΔRESPL and ΔThreshold are shown at each audiometric frequency. A linear regression line shows the predictive relationship between the variables. The figure shows that difference in hearing thresholds between the transducers (ΔThreshold) can be explained by the difference in the ΔRESPL between the transducers. Pearson's correlation coefficient (*r*) and *p*-value are presented on the top left corner of the plots.

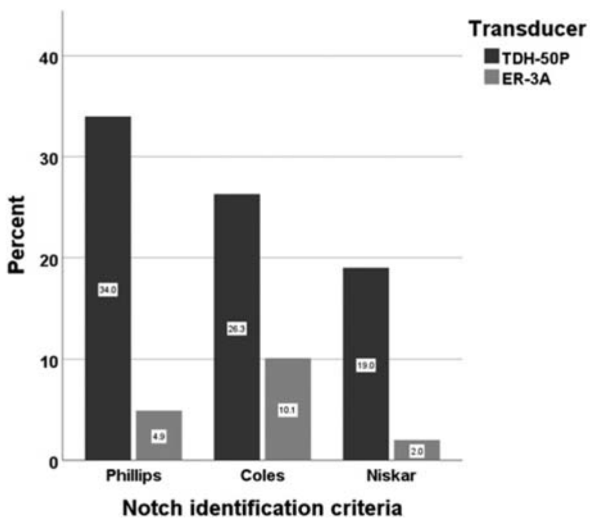

Fig. 4 Percentage of notched audiograms in the study sample identified using Phillips', Coles', and Niskar's criteria for hearing thresholds obtained with ER-3A and TDH-50P receivers.

and 8000 Hz explained a substantial proportion of variance in the measurement of notched audiograms, where Cox and Snell R^2 was estimated to be 0.45.

A binary logistic regression analysis ($N_{RESPL\_ears} = 64$) was performed to list predictors for notched audiograms identified using Coles' criteria for hearing thresholds obtained with TDH-50P receivers. The analysis revealed that RESPLs at 6000 Hz (OR: 0.625 [95% CI: 0.493-0.793], $p = 0.0001$) and 8000 Hz (OR: 1.313 [95% CI: 1.104-1.562], $p = 0.002$) showed significant association with the notched audiogram. These dependent variables explained a substantial proportion of variance in the measurement of notched audiograms, where Cox and Snell R^2 was estimated to be 0.481.

A binary logistic regression analysis ($N_{RESPL\_ears} = 64$) was performed to list predictors for notched audiograms identified using Niskar's criteria for hearing thresholds obtained with TDH-50P receivers. The analysis revealed that RESPLs at 6000 Hz (OR: 0.69 [95% CI: 0.565-0.844], $p = 0.0002$) and 8000 Hz (OR: 1.205 [95% CI: 1.04-1.395], $p = 0.013$) showed significant association with the notched audiogram. These dependent variables explained a substantial proportion of variance in the measurement of notched audiograms, where Cox and Snell R^2 was estimated to be 0.395.

The number of notched audiograms for hearing thresholds obtained using ER-3A receivers with Phillips', Coles', and Niskar's criteria were 4/64, 6/64, and 1/64, respectively. The regression analyses were performed for Phillips' and Coles' criteria with two independent variables: RESPLs at 6000 and 8000 Hz. The independent variables revealed no significant association ($p < 0.05$) with the notch. The regression analysis could not be performed for notches identified with Niskar's criteria.

Relation between Notched Audiograms and DPOAEs

A repeated measure ANOVA($N_{DPOAE\_ears} = 170$) was performed to determine the relation between DPOAEs and notched audiograms at three stimulus levels: 55/40, 65/55, and 75/75 dB SPL. The adjusted p-value ($p = 0.05/3 = 0.016$) threshold with Bonferroni correction was used as a threshold for statistical significance. For the TDH-50P receivers, the ANOVA models were calculated for notched audiograms identified using Phillips', Coles', and Niskar's definitions. For Phillips' notch identification criteria, the results revealed that DPOAEs were not significantly different between individuals with notched audiograms and without notched audiograms at primary levels 55/40 [$F_{(1, 168)} = 2.117$, $p = 0.148$], 65/55 [$F_{(1, 168)} = 0.242$, $p = 0.242$], and 75/75 [$F_{(1, 168)} = 1.117$, $p = 0.292$]. For Coles' notch identification criteria, DPOAEs were not significantly different between the groups for stimulus levels at 55/40 [$F_{(1, 168)} = 3.16$, $p = 0.07$], at 65/55 [$F_{(1, 168)} = 2.047$, $p = 0.154$], and at 75/75 [$F_{(1, 168)} = 4.316$, $p = 0.039$]. Similar results were obtained for Niskar's criteria where DPOAEs were not significantly different between the groups for the stimulus levels 55/40 [$F_{(1, 168)} = 1.119$,

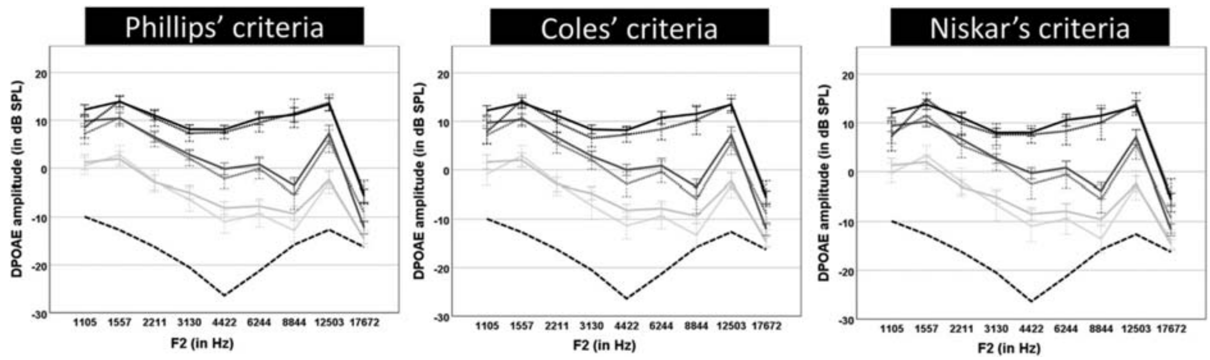

Fig. 5 DPOAE levels as a function of F_2 frequency for the notch identification performed using Niskar's, Coles', and Phillips' criteria for hearing thresholds obtained using TDH-50P receivers. The solid lines present DPOAE levels for individuals with no notched audiograms, and dashed lines present DPOAE levels for individuals with notched audiograms. The black, dark gray, and light gray lines present the average DPOAE amplitudes obtained with the combinations of primary tones 75/75, 65/55, and 55/40, respectively. Dark dash line presents the average noise floor. Error bars indicate 95% CI.

$p = 0.292$], 65/55 [$F_{(1,\ 168)} = 0.781$, $p = 0.378$], and 75/75 [$F_{(1,\ 168)} = 2.018$, $p = 0.157$]. ►**Figure 5** presents DPOAE data between individuals with notched audiograms and no notched audiograms for three notch identification criteria obtained using TDH-50P receivers. The prevalence of notched audiograms for hearing thresholds obtained using ER-3A receivers with Phillips', Coles', and Niskar's criteria were 7/170, 17/170, and 2/170, respectively. Therefore, the repeated measure ANOVA could not be performed on the data.

Relation between Notched Audiograms and Length of EAC

Independent sample t-tests ($N_{EAClength\_ears} = 70$) were performed to determine the relation between notched audiograms an d EAC length. For the TDH-50P receivers, the t-test statistics were calcul ated for notched audiograms identified using Phillips', Coles', and Niskar's definitions. The results showed that individuals with notched audiograms exhibited significantly shorter EAC length than individuals with no notch for Phillips' [$MD = 0.198$ cm, $t_{(68)} = 2.141$, $p = 0.036$] and Coles' [MD = 0.239 cm, $t_{(68)} = 2.26$, $p = 0.027$] criteria (►**Figure 6**). No such group difference was obtained for Niskar's criteria [MD = 0.143 cm, $t_{(68)} = 1.238$, $p = 0.22$]. The t-test results were likely to be influenced by a lower prevalence of notched audiograms (i.e., 11/70 participants) identified using Niskar's criteria. A significant negative correlation coefficient was present between the hearing threshold at 6000 Hz obtained with TDH-50P headphones [r (70) = −0.294, $p = 0.013$] and EAC length. A significant positive correlation co efficient was obtained between the RESPL at 6000 Hz obtained with TDH-50P headphones [r (64) = 0.54, $p = 0.038$] and EAC length. The correlation coefficient was not significant between the hearing threshold at 6000 Hz obtained with ER-3A receivers and EAC length [r (70) = -0.07, $p = 0.56$]. The coefficient was significant between the RESPL at 6000 Hz obtained with ER-3A receivers and EAC length [r (64) = 0.56, $p = 0.028$].

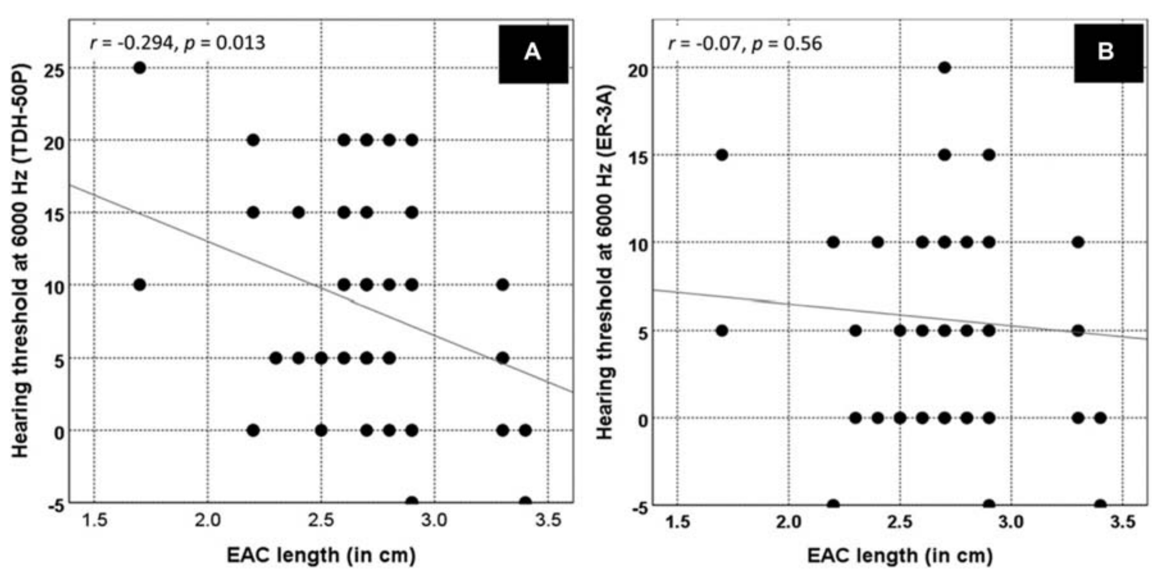

Fig. 6 Scatter plots between the EAC length and hearing thresholds at 6000 Hz obtained with TDH-50P (A) and ER-3A (B) receivers are shown. A linear regression line shows the predictive relationship between the variables. Pearson's correlation coefficient (r) and p-value are presented on the top left corner of the plots.

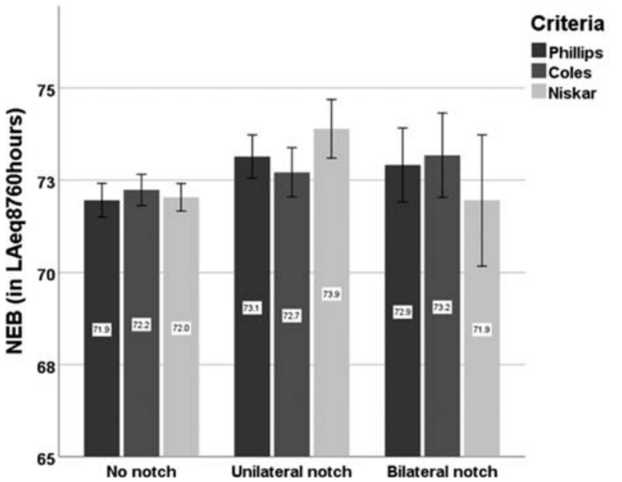

Fig. 7 NEB for individuals with no notch, unilateral notch, and bilateral notch for the notch identification performed using Niskar's, Coles', and Phillips' criteria for hearing thresholds obtained using TDH-50P receivers. NEB was not significantly different between the experimental groups.

Relation between Notched Audiograms and NEB

Noise Exposure Questionnaire was used to estimate NEB. The questionnaire did not estimate an ear-specific NEB score. The study participants were categorized into three groups for each transducer type to investigate the relationship between notched audiogram and NEB: no notch, unilateral notch, and bilateral notch. The analysis was performed on 95 participants with complete survey and audiometric data ($N_{survey\_participants} = 95$). ►**Figure 7** presents average NEB scores for individuals with no notch, unilateral notch, and bilateral notch for hearing thresholds obtained with TDH-50P receivers. A one-way ANOVA model was used to identify the relation between NEB and notched audiograms. The analysis revealed no significant main effect for NEB and notched audiograms identified using Phillips' [$F_{(2,\ 92)} = 1.364$, $p = 0.26$], Coles' [$F_{(2,\ 92)} = 0.437$, $p = 0.64$], and Niskar's [$F_{(2,92)} = 2.76$, $p = 0.068$] notch identification criteria. The prevalence of notched audiograms was substantially low for hearing thresholds obtained with ER-3A receivers. Therefore, the inferential statistical analysis for investigating the relation between notched audiograms and NEB was not performed.

Discussion

The major findings of the study were (a) the prevalence of notched audiograms was substantially higher when TDH-50P receivers were used to measure hearing thresholds than when ER-3A receivers were used; (b) RESPLs at 6000 and 8000 Hz were the major predictors of notched audiograms when TDH-50P receivers were used to measure hearing thresholds; (c) the notched audiograms obtained with TDH-50P receivers showed no association with NEB; and (d) individuals with notched audiograms measured using TDH-50P did not show convincing evidence of cochlear dysfunction as assessed by DPOAEs. Individuals with notched audiograms obtained with TDH-50P receivers revealed an average of the shorter EAC and a poorer hearing threshold at 6000 Hz. The results showed that the outer-ear resonance characteristics could mimic a notch-like pattern in the audiogram when TDH style receivers were used to measure hearing thresholds. Most participants exhibiting a notch audiogram using TDH-50P headphones revealed a flat audiometric configuration when ER-3A 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 supra-aural and insert receivers were substantially different (Valente et al[59]), which might influence hearing threshold measurement at high frequencies (McBride and Williams[31]; Lawton[22]; Schlauch and Carney[47]; Schlauch and Carney[48]). Therefore, supra-aural receivers should not be used to investigate NIHL in young adults, especially when less restrictive notch identification criteria are used.

Influence of Notched Audiograms on DPOAEs

DPOAEs provide a window into the cochlear mechanical function. DPOAEs are generated when two traveling waves on the basilar membrane, elicited by two tones at closely spaced frequencies, interact and undergo intermodulation distortion. This produces distortion products in the basilar membrane vibratory response, which travels backward from the cochlea to the TM. DPOAEs measured close to the TM include reflection and distortion components generated by the cochlea in response to processing the primary tones. Noise exposure that damages outer hair cells (OHCs) reduce auditory sensitivity, make cochlear processing more linear, and diminish DPOAEs (e.g., Stover et al[55]; Marshall et al[29]). OHCs are one of the vulnerable cochlear structures to noise-induced damage (Nordmann et al[41]). Research suggests that DPOAEs are more sensitive to noise-induced cochlear insult based on observations that they sometimes diminish or disappear even when behavioral hearing thresholds remain unchanged (Engdahl and Kemp[15]; Attias et al[3]; Marshall et al[30]). Therefore, the present study used DPOAEs to evaluate noise-induced cochlear damage. DPOAEs were elicited using 55/40, 65/55, and 75/75 primary tones. The 55/40 primary tone combination is considered most sensitive in detecting noise-induced cochlear damage (Kummer et al[21]; Poling et al[45]). The average DPOAE amplitudes for individuals with notched audiograms using TDH-50P failed to achieve the statistical significance even at the 55/40 primary tone combination. ►**Figure 5** suggests that the average DPOAE amplitudes for individuals with the notched audiograms were lower than their counterparts at F_2 ranging from 3000 to 8000 Hz, indicating that some participants with the notched audiograms may exhibit cochlear damage. However, it appears that the group difference did not achieve statistical significance because of the high false-positive rate in the notch identification process. Recent evidence suggests that noise exposure can induce cochlear dysfunction at high frequencies even when hearing thresholds and DPOAEs remain unchanged at the conventional frequency range (250-8000 Hz) (Liberman et al[26]). The present study measured DPOAEs up to 16000 Hz. However, DPOAEs revealed no significant group difference between individuals with no notch and with notched audiograms. This evidence indicates that a major portion of the notched audiograms observed in the present investigation was not associated with noise-induced cochlear damage.

RESPL Variation in the Calibrated Clinical Audiometers and Audiometric Notch

National and international bodies have laid out standards for audiometric calibration that include standard operating procedures and use of standardized equipment to carry out the calibration process for improving accuracy, reliability, and validity of the audiometric measures (e.g., BSI[8]; IEC[19]; ANSI[2]; BSA[7]). A previous study assessed the performance of calibrated audiometers with TDH-39 receivers using a Bruel and Kjaer head and torso simulator, accurately replicating the average size of adult human ears, head, and torso (Barlow et al[4]). The study found high variability in the sound pressure level at the simulated TM generated by calibrated audiometers. The highest variability was obtained at 6000 Hz with the maximum variation of sound pressure level for the same tone presentation was 21 dB. The study found that calibrated audiometers could produce high variability even in a head and torso simulator when supra-aural headphones were used for hearing threshold measurements. High variability in the performance of calibrated audiometers might be influenced by different supra-aural headband designs that exert different magnitudes of force on the transducers. Standard audiometric calibration techniques require a static force of 4.5 N ($\pm$ 0.5 N) rather than using tension from the headphone band. The force exerted on the headphone in clinical situations is likely to be variable and would be influenced by headband design, head size, and headphone placement. The variation in the force exerted on the transducers between clinical situations and calibration procedure might be an important factor causing the high variability observed in the RESPL around 6000 Hz that can result in the high prevalence of notched audiograms.

Audiometric Notch and Standing Waves in the Ear Canal

Standing waves can produce spatially nonuniform sound pressure levels for frequencies more than 2000-3000 Hz, leading to large errors in the sound pressure at the TM (Siegel[52]). The standing waves in the EAC can influence baseline audiometric thresholds (Dirks et al[14]; Lawton[22]). It was suggested that individuals with a shorter EAC would exhibit reduced RESPLs and a notched audiometric configuration because of the influence of standing waves in the EAC (Dirks et al[14]; Lawton[22]). The present study found that individuals with a shorter EAC revealed lower RESPLs, poorer hearing thresholds at 6000 Hz, and subsequently higher prevalence of notched audiograms when TDH-50P headphones were used to measure hearing thresholds (►**Figure 6A**). This observation is consistent with Dirks et al[14] and Lawton.[22] The correlation coefficient between the EAC length and RESPL at 6000 Hz obtained with ER-3A receivers was significant. Surprisingly, the study obtained no significant correlation coefficient between the hearing threshold at 6000 Hz obtained with ER-3A receivers and EAC length (►**Figure 6B**). This observation may be explained by high variability in the behavioral hearing threshold at 6000 Hz. RESPLs and hearing thresholds obtained with ER-3A receivers were less variable than TDH-50P receivers (see ►**Figure 2**). Besides, age-related morphometric changes in the external ear are likely to influence the acoustic characteristics of the external ear (e.g., Niemitz et al[37]; Pandit et al[42]) and subsequently may affect audiometric calibration. The present study reiterates the importance of reducing variability in RESPLs for accurately estimating the prevalence of NIHL in children and young adults (e.g., Valente et al[59]; Valente et al[58]; Lawton[22]; Schlauch and Carney[47]; Schlauch and Carney[48]; Bhatt and Guthrie[6]).

Prevalence of NIHL and the National Health and Nutrition Examination Survey (NHANES)

The NHANES is a population-based cross-sectional survey that includes a household interview and health-related assessments to investigate the health and nutritional status of a noninstitutionalized population of the United States (CDCP[10]). It includes a state-of-the-art research protocol to estimate health-related outcomes in children and adults across the United States. The NHANES has used supra-aural headphones to measure hearing thresholds. Therefore, studies using audiometric data from the NHANES have reported a high prevalence of NIHL in young adults, notably when the NIHL identification criteria included a hearing threshold at 6000 Hz (e.g., Niskar et al[39]; Niskar et al[38]; Shargorodsky et al[50]; Henderson et al[18]; Bhatt and Guthrie[6]). NIHL prevalence was reported to be substantially lower when the notch identification criteria did not include a hearing threshold at 6000 Hz (e.g., Agarwal et al[1]; Mahboubi et al[28]).

Analysis of NHANES data (2005-2010) revealed that individuals aged 14–15 years showed a higher prevalence of notched audiograms, despite reporting lower exposure to noise and music than individuals aged 18-19 years (Bhatt and Guthrie[6]). The present study suggests that individuals aged 14–15 years were likely to exhibit shorter EACs leading to a higher prevalence of notched audiograms than individuals aged 18–19 years. Similarly, Su and Chan[56] found that the prevalence of NIHL in noninstitutionalized young adults remained unchanged from 1988 to 2010 (NHANES, 1988–2010), despite an overall rise in exposure to loud noise or music through headphones. The present study suggests that the audiometric data obtained with the supra-aural receivers were influenced by standing waves in the EAC, which could lead to a higher prevalence of notched audiograms in the absence of noise-induced cochlear damage. The prevalence ofnotched audiograms might have remained unchanged from 1988 to 2010 because a major portion of the notched audiograms was influenced by the calibration error in RESPL values rather than noise-induced cochlear dysfunction.

Possible Solutions to Accurately Estimating the NIHL Prevalence in Children and Young Adults

Accurate measurement of high-frequency thresholds is a critical factor influencing the prevalence of NIHL in children and young adults (Schlauch and Carney[48]). The present study showed that supra-aural receivers could produce a notch-like pattern in the absence of noise-induced cochlear dysfunction that can obscure the accurate estimation of NIHL. The effects of outer-ear resonance on the final spectrum delivered to the EAC are critically dependent on the impedance of the transducer. The impedance of TDH-50P (60 Ω) is highest among the other variants of TDH headphones, such as TDH-39P (10 Ω) and TDH-40P (10 Ω). It can be argued that the use of lower impedance variants of TDH headphones would increase the RESPL at 6000 Hz and reduce the occurrence of spurious notches. However, the literature suggests that the prevalence of notched audiograms remains high when lower impedance variants of TDH headphones are used to measure hearing thresholds (e.g., Niskar et al[38]; Schlauch and Carney[48]; Flamme et al[16]; Bhatt and Guthrie[6]). Therefore, it is recommended to avoid the use of supra-aural transducers for measuring hearing thresholds when investigating NIHL in children and young adults. Bhatt and Guthrie[6] argued that deeper notches might be less prone to calibration error and subsequently to a high false-positive rate, suggesting that 6000 Hz should be weighted differently than the others to reduce the influence of calibration error on notch identification. However, notch definitions that require high notch depth might compromise the sensitivity of the audiometric testing in identifying early indications of NIHL.

Insert receivers can reduce the influence of the notch artifact because they are placed closer to the TM than the supra-aural receivers. The insert receiver can be a better choice for measuring hearing thresholds when investigating NIHL in children and 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[25]) or forward pressure level (Neely and Gorga[36]; Scheperle et al[46]). 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[53]). Therefore, research efforts should be directed to estimate prevalence and risk factors of NIHL using methods that are least influenced by the standing waves in the EAC.

Conclusions

The current study described the effects of supraaural and insert receivers for estimating the prevalence of NIHL in young adults. NIHL prevalence was influenced by RESPLs at 6000 and 8000 Hz when TDH-50P receivers were used to measure hearing thresholds. The notched audiograms that are widely used to measure NIHL prevalence were associated with the error in RESPL values at high frequencies. The calibration errors across the audiometric frequencies were found to mimic a notch-like pattern in the absence of noise-induced cochlear damage. Therefore, the supraaural receivers should not be used to estimate the prevalence of NIHL in children and young adults when less restrictive notch identification criteria are used to identify NIHL. Further research is required to quantify the effects of gender and morphological variations of the outer ear on audiometric thresholds, RESLPs, and audiometric notch.

Abbreviations

ANOVA	analysis of variance
DPOAE	distortion product otoacoustic emission
EAC	external auditory canal
NEB	noise exposure background
NHANES	National Health and Nutrition Examination Survey
NIHL	noise-induced hearing loss
OR	odds ratio
RESPL	real-ear sound pressure level
RETSPL	real-ear threshold sound pressure level
TM	tympanic membrane

Conflict of Interest
None declared.

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