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Extended High Frequency Thresholds in College Students: Effects of Recreational Noise

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Abstract

Background—Human hearing is sensitive to sounds from as low as 20 Hz to as high as 20,000 Hz in normal ears. However, clinical tests of human hearing rarely include extended high frequency (EHF) threshold assessments, at frequencies extending beyond 8,000 Hz. EHF thresholds have been suggested for use monitoring the earliest effects of noise on the inner ear, although the clinical utility of EHF threshold testing is not well established for this purpose.

Purpose—The primary objective of this study was to determine if EHF thresholds in healthy, young adult college students vary as a function of recreational noise exposure.

Research Design—A retrospective analysis of a laboratory database was conducted; all participants with both EHF threshold testing and noise history data were included. The potential for "pre-clinical" EHF deficits was assessed based on the measured thresholds, with the noise surveys used to estimate recreational noise exposure.

Study Sample—EHF thresholds measured during participation in other ongoing studies were available from 87 subjects (34 male and 53 female); all participants had hearing within normal clinical limits (≤25 HL) at conventional frequencies (0.25 to 8 kHz).

Results—EHF thresholds closely matched standard reference thresholds [ANSI S3.6 (1996) Annex C]. There were statistically reliable threshold differences in subjects that used music players, with 3–6 dB worse thresholds at the highest test frequencies (10–16 kHz) in participants that reported long-term music player device use (longer than 5 years), or higher listening levels during music player use.

Conclusions—It should be possible to detect small changes in high frequency hearing for patients/participants that undergo repeat testing at periodic intervals. However, the increased population-level variability in thresholds at the highest frequencies will make it difficult to identify the presence of small but potentially important deficits in otherwise normal hearing individuals that do not have previously established baseline data.

Keywords

extended high frequency; EHF; music; hearing loss; personal music player

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Human hearing has long been known to extend to at least 20,000 Hz (Fowler & Wegel, 1922; for reviews, see De Seta et al., 1985; Vogel et al., 2007). The frequency range from 10 to 20 kHz is now commonly referred to as the ultra-audiometric or “extended high frequency” (EHF) range of hearing. Elevated EHF thresholds have been linked with a history of noise exposure (Vassallo et al., 1968; Osterhammel, 1979; Erickson et al., 1980; Fausti et al., 1981a; Fausti et al., 1981b). Significant EHF deficits have also been reported in patients treated with ototoxic drugs such as the angioplast cisplatin (Fausti et al., 1984b; Tange et al., 1985) and aminoglycoside antibiotics (Fausti et al., 1984a). Consequently, EHF testing has been proposed as a potentially useful assay for identifying early changes in hearing following either physical or pharmacological trauma, thus providing an “early” warning for subsequent hearing loss.

Serial monitoring at EHF frequencies has been successfully applied for detecting the early onset of drug-induced ototoxicity (see, for example, Fausti et al., 1999; Vaughan et al., 2002; Knight et al., 2007; Konrad-Martin et al., 2010; Jacobs et al., 2012). Longitudinal studies assessing EHF thresholds as a function of noise, by contrast, are much more limited. Data from a single longitudinal study that followed a sample of 14-yr old students over a three-year time course revealed the largest threshold changes occurred between test 1 (at 14-yrs old) and test 2 (at 15-yrs old); the largest changes were 4 to 6 dB, and these threshold shifts were observed at the two highest frequencies tested (14 and 16 kHz) (Serra et al., 2005). Based on reported exposures, changes in hearing were attributed to music coming from a variety of sources, including live concert attendance and attendance at discothèques (Biassoni et al., 2005). Whereas serial studies are limited, cross-sectional studies are more common, and the most robust support for noise-induced deficits at EHF frequencies comes from a cross-sectional analysis of hearing thresholds in adult male factory workers, with varied exposure to noise (Ahmed et al., 2001). When the analysis was limited to just those workers with “normal” (≤20 dB HL) thresholds from 250 Hz to 8 kHz, the subset of workers exposed to noise had deficits at EHF frequencies from 12 to 20 kHz, whereas other workers not assigned to noisy areas did not have EHF threshold deficits. These data were taken to suggest EHF threshold deficits precede hearing loss at lower frequencies. Longitudinal studies, incorporating serial monitoring, are critical for determining whether workers with EHF deficits go on to develop hearing loss at lower frequencies over time. However, the cross-sectional data are both important and intriguing with respect to the utility of EHF deficits in providing an “early warning”. Changes at EHF frequencies may ultimately prove to be a useful tool for identifying individuals with increased vulnerability to noise insult (see Osterhammel, 1979), or those likely to develop noise-induced hearing loss (NIHL) at conventional test frequencies (250 Hz to 8 kHz).

The potential for changes at EHF frequencies have subsequently been explored in adolescents exposed to recreational music, an alternative source of sound overexposure. Use of personal music players has already been correlated with EHF deficits (Peng et al., 2007; Figueiredo et al., 2012); our own analysis of the relationship between thresholds at conventional test frequencies, ranging from 250 Hz to 8 kHz, is consistent with this literature in that deficits as a function of music player were observed only at the highest conventional test frequencies (6 and 8 kHz) (Le Prell et al., 2011). One of the main shortcomings of the existing literature that seeks to identify relationships between music

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player use and hearing deficits is the limited information on other sources of noise to which study participants are routinely exposed. Since our earlier report, we have continued to screen young adult hearing thresholds such that we now have access to EHF thresholds from a significant number of individuals who have participated in completed (Le Prell et al., 2012) and ongoing studies. Our noise survey yields information not only about music player use, but also concert attendance, attendance at loud sporting events, attending bars/clubs, playing a musical instrument, etc. Here, we test the hypothesis that recreational noise exposure is reliably related to “pre-clinical” changes in hearing, in the form of elevated EHF thresholds in young adults who report the greatest level of noise exposure.

Materials and Methods

Participants

EHF (10, 12.5, 14 and 16 kHz) thresholds were available from 87 young adult college students with hearing thresholds of 25 HL or better from 250 Hz to 8 kHz, as assessed during IRB-approved studies conducted from 2008 to 2012 (see Table 1 for demographic data). All participants had responded to advertisements posted on the University of Florida campus inviting “normal-hearing” young adults (ages 18–31) to participate in hearing studies. Prospective participants provided written informed consent, and were compensated $10–$15 per hour for their time. All protocols and procedures were approved by the appropriate Institutional Review Board (IRB) at the University of Florida.

Surveys

Participants completed health (Table 1) and hearing-related (Table 2) surveys after providing written informed consent. Because the study participants were drawn from two different study-specific volunteer populations, there was a subtle difference with respect to questions posed. In the first study population, participants were asked to report which loud sounds they are exposed to during their leisure time, including Bars/Clubs, Concerts/Discos, Walkman/iPod, Loud Music in a Vehicle, Hunting/Shooting Range, Sports Events, or other. There was no additional descriptive detail for any reported exposures. In the second study population, participants were asked which loud sounds they are typically exposed to in their leisure time, with the additional specification of once/month or more often; however, the same list of common exposures was provided. Survey responses are pooled here to provide a comprehensive array of common noise sources across the entire sample. Participants enrolled in this second study completed additional detailed questionnaires specific to musical instrument practice patterns, and personal music player use patterns. Data from the 54 participants who completed the more detailed surveys are provided in the bottom half of Table 2.

Screening Procedures

Participants were asked to avoid loud sound for 48 hours prior to hearing screening. The screening tests included otoscopy to ensure normal external ear anatomy and the absence of obstructive debris such as occluding cerumen, followed by tympanometric testing and conventional pure-tone air conduction threshold testing from 250 Hz to 8 kHz. To proceed to the EHF testing protocol, subjects were required to pass both the otoscopic examination

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and tympanometric testing. Normal middle ear pressure and compliance was defined by tympanometric configurations with middle ear pressure (MEP) values from −140 to +40 daPa (based on the 90% range for adults, see Margolis & Hunter, 2000), compliance (Peak Ytm) values from 0.3 to 1.8 ml, and ear canal volume (Vea) values from 0.8 to 2.1 cm^3. Participants were required to have air conduction thresholds no worse than 25 dB HL from 0.25 – 8 kHz. In addition, inclusion criteria required that thresholds for the right and left ears be no more than 15 dB HL apart. Finally, if air conduction thresholds were 15 dB HL or higher (worse), bone conduction testing was administered and the difference between air and bone thresholds was required to be 10 dB or less (see Le Prell et al., 2011; Le Prell et al., 2012). All of the participants described in this report met the aforementioned inclusion criteria. Participants who did not meet these criteria did not proceed to EHF testing. Approximately 20% of screened participants failed to meet the above criteria (Le Prell et al., 2011; 2012); it is worth noting that a previous study (Mills et al., 1979) had to screen 149 college student participants in order to find 60 subjects with thresholds of 10 dB HL or better (a 60% failure rate).

Audiometric threshold measurement was conducted using a Grason-Stadler model 61 (GSI 61) audiometer calibrated to ANSI 3.6 1996 with high frequencies calibrated according to Annex C. Participants were tested in a double-walled sound-treated test booth meeting ANSI/ASA S3.1-1999 (R2008) specifications for audiometric test rooms. Pure-tone air conduction thresholds were obtained using EAR 3A insert earphones for test frequencies of 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz, and Sennheiser HDA200 circum-aural headphones for test frequencies of 10, 12.5, 14, and 16 kHz. For each test frequency, the initial presentation level was 30 dB HL after which the intensity was decreased in 10-dB steps until the participant failed to respond. Presentation levels were then increased in 2-dB steps after each missed tone presentation, until correct responses were observed. Levels were then decreased by 6-dB after correct detection responses. Ascending runs using 2-dB increments were repeated three times, and threshold was operationally defined as the lowest level at which responses were obtained on two out of three ascending runs. Reliability was assessed using repeated tests at 2 and 8 kHz in each ear. Responses were considered reliable if the difference between test and retest thresholds was no more than 5 dB (a criterion previously used by Fausti et al., 1999). Only one subject was unable to meet the 5-dB test-retest criterion and was excluded from further assessment. All subjects contributing data to this report met the 5-dB test-retest criterion.

Statistical Analyses

Descriptive and inferential analyses of differences associated with the independent variables were conducted using SPSS version 20. For categorical data, the distribution of participants across groups was evaluated using the Pearson Chi-square statistic; Fischer’s exact test was used if sample size per cell was less than 5 in any cell. Normality of the distribution was assessed using the Levine test. Tests comparing paired data sets (such as right ear versus left ear comparisons) were conducted using paired-sample two-tailed t-tests if Levine tests indicated that the data were normally distributed. The Wilcoxin signed-rank test for related samples was used if the normality assumption was violated. Comparisons of two independent samples (such as male versus female) were conducted using two-tailed

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independent samples t-tests if the Levine tests revealed the data were normally distributed or the Mann Whitney U test was used if the normality assumption was violated. When there were more than two-levels of an independent variable, inferential comparisons were conducted using one-way analysis of variance (ANOVA) if the Levine tests revealed the data were normally distributed or the Kruskal Wallis test if the normality assumption was violated. A criterion of $\alpha = .05$ was used for all analyses to determine significant effects. Inferential comparisons to assess effects of noise on threshold sensitivity were conducted for: total number of noise sources reported, individual noise sources (concerts, bars/clubs, sporting events, music player use, loud music in a vehicle, musical instrument use), and patterns of music player use (hours per day, days per week, years of use, background noise conditions).

Results

Participant Demographics: No Important Sex Differences

Descriptive characteristics are summarized in Table 1. There was no reliable difference in age of subjects when males and females were compared; however, males were generally taller and weighed more than females ($p \leq 0.05$). There were no reliable differences in the distribution of “yes” responses on any of the categorical variables when males were compared to females. Tobacco use was minimal in both males and females, and the majority of male and female participants reported consumption of 0–5 alcoholic beverages per week. Of the participants, 23–24% reported a history of ear infections, percent yes responses increased to 47–53% when participants were asked if they had ever had an ear infection. None of the participants reported an ear infection within the past 3 months. There were 15–18% percent reporting a history of tinnitus; the proportion of participants reporting ever experiencing tinnitus after noise exposure was higher (53%–62%). Of those participants who reported experiencing tinnitus after noise, 50% reported tinnitus in the absence of noise as well. There were smaller numbers of participants reporting hyperacusis, history of ear pain or ear drainage, balance issues, seizures, frequent or severe headaches, fainting, disorientation, relatives with hearing loss, or any previous hearing loss. Of the 5 participants that reported ever experiencing any hearing loss, all 5 reported the hearing loss had only occurred after loud sound exposure.

Participant Noise History

Noise history is summarized in Table 2. For the total participant pool, there was no reliable difference with respect to total number of sound exposure sources reported by males and females, and there was no reliable difference with respect to any previous impulse noise exposure. The most commonly reported sources of loud sound exposures were personal music players (note that 56% reported the device was a frequent source of loud sound exposure, while 90% reported use of a device), followed by bar/club attendance (41% yes) and loud music played in vehicles (33% yes). A number of participants reported attending loud sporting events (21% yes) or concerts (21% yes). A smaller subset of participants reported music rehearsal (6% yes), workplace noise (5% yes), or firearms use (1% yes). The only source of exposure with a statistically reliable difference in the distribution of male and female participants reporting frequent loud sound exposure was music rehearsal, with 15%

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of males reporting yes compared to 0% of females (Pearson Chi-Square = 8.269, df = 1, p = 0.008). Male participants were the only ones to specifically report "yes" when asked if music rehearsal was a frequent loud sound exposure; however, there were female musicians in the participant pool. Among the subset of participants completing more detailed questionnaires about musical instrument use, there was a statistically reliable difference (Pearson Chi-Square = 4.517,df = 1, p = 0.047) between males and females with respect to playing an instrument, with 29% of males responding "yes" and 11% of females responding "yes". Within those who played instruments, there was no sex difference in the distribution of responses regarding hours per day of solo practice, hours per day of group practice, years of playing experience, or type of instrument played.

Personal music players were the most common source of exposure, reported by more than half of the participants. Among the subset of participants completing more detailed questionnaires about personal music player use, participants were surveyed regarding both use of the device, as well as hours of device use per day, days of device use per week, and years of device use. Although preferred listening level was not measured, participants did report whether they used their device in noisy areas, quiet areas, or both, and also reported whether they could hear someone speaking to them while using the device. There were no statistically reliable differences in the distribution of the participants' responses as a function of sex in any of the above categories.

Comparisons with existing normative literature

In this report, EHF thresholds from healthy young adults with hearing thresholds of 25 dB HL or better from 250 Hz to 8 kHz were consistent with the RETSPLs specified in Annex C of ANSI S3.6 (American National Standards Institute, 1996) (Figure 1A), as well as EHF thresholds for similarly aged subjects as described in other recent reports (Figure 1B). The observed increase in standard deviation with increasing frequency is consistent across studies (Figure 1B). That normative data derived from fairly large samples [100 subjects tested by Frank (2001) and the data from the 87 participants described here] are highly consistent across laboratories is an encouraging finding with respect to the development of normative databases.

Ear, sex, and age

Right and left ear thresholds were highly correlated (Spearman's Rho values ranging from 0.483–0.742, all $p < 0.01$); the only statistically reliable differences between right and left ear thresholds were at 4 and 6 kHz ($p \leq 0.05$; Wilcoxon Signed Rank Test). Right ear thresholds were 1–1.5 dB better than left ear thresholds at those two frequencies (see Figure 2A). To reduce the effect of random test-retest variability and explore patterns of change, pure-tone-thresholds are often averaged at subsets of the lower and higher test frequencies during post-hoc analysis (see Niskar et al., 1998; Agrawal et al., 2008; Shargorodsky et al., 2010; Henderson et al., 2011). When pure-tone average thresholds were considered (LFPTA: 0.5, 1 and 2 kHz; HFPTA: 3, 4, and 6 kHz; EHFPTA: 10, 12, 14 and 16 kHz), there were no reliable differences between right and left ears (see Figure 2B; note that all PTA thresholds are plotted in dB HL). Given robust right-left correlations and small right-left asymmetries, thresholds for right and left ears were averaged for all subsequent

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analyses, such that each subject contributed a single survey response (per question) and a single average threshold (at each test frequency and for each pure-tone average).

Male subjects had higher (worse) thresholds than female subjects at 0.5, 3, 4, and 6 kHz, as well as at 10 and 12 kHz (all $p \le 0.05$) (Figure 2C). Differences were relatively small, with male thresholds being ~3 dB worse than female thresholds. Differences in PTA thresholds were statistically reliable for the HFPTA comparison ($p \le 0.05$), but not LFPTA or EHFPTA comparisons ($p > 0.05$; see Figure 2D).

The possibility of age-related differences in threshold sensitivity was assessed using the age categories described by Green et al. (1987), who reported ~10 dB threshold differences during EHF tests of 18–20 year old subjects versus 21–23 year old subjects, with an additional deficit of ~20 dB in 24–26 year old subjects compared to 21–23 year old subjects. Here, the only frequency at which thresholds differed as a function of age was 8 kHz ($p \le 0.05$), with thresholds increasing by 2–3 dB with increasing age bin (see Figures 2E and 2F).

Effects of individual noise sources on hearing

There was no statistically reliable relationship between either single-frequency threshold or PTA threshold and noise history when the analysis was based on a “total” risk metric (assessed as the total number of insults reported, which ranged from 0 to 6) (Figures 3A, 3B). When risk of any single insult was considered (i.e., thresholds of those reporting concert attendance compared to those that do not report attending concerts), there was no statistically reliable relationship between any individual noise insult and either single-frequency threshold or PTA threshold (all p values > 0.05).

Effects of music player use on hearing: detailed analysis

There was no statistically reliable relationship between either PTA threshold or single-frequency threshold and music player use when it was dichotomized as a yes/no variable (not shown). Because only the subset of users that choose higher listening levels and/or longer listening durations are likely to be at risk for hearing loss, thresholds were evaluated for potential relationships with hours of device use per day, days of device use per week, and years of device use. There were no statistically reliable relationships between PTA thresholds or thresholds at single test frequencies using any of these metrics (not shown). Because robust group differences have been reported for subjects that have used music players for 5 years or longer (Peng et al., 2007), long-term device users were compared to shorter term users and nonusers. Using the same 5-year criteria as Peng et al. (2007), there were no LFPTA or HFPTA differences and no threshold differences at any individual frequency at or below 8 kHz. However, there was a statistically significant group difference using the EHFPTA metric ($p \le 0.05$; see Figure 4A). At and above 10 kHz, there were small but statistically reliable elevations in thresholds in those that had used the devices for longer periods of time compared to non-users and those that had used the devices for shorter periods of time, with 3–4 dB deficits at 10 and 12.5 kHz (10 kHz: $p \le 0.05$; 12.5 kHz: $0.5 < p \le 0.10$), and 6–7 dB deficits at 14 and 16 kHz (14 kHz: $p \le 0.05$; 16 kHz: $0.5 < p \le 0.11$) (Figure 4B).

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Although preferred listening level was not measured, subjects did report whether they used their device in noisy areas, quiet areas, or both, and they also reported whether they could hear someone speaking to them while using the device. Subjects that used their devices in noisy backgrounds had worse EHPTA thresholds than subjects that used their devices in quiet backgrounds (Figure 4C). Single-frequency analyses revealed statistically reliable differences at 12, 14, and 16 kHz (Figure 4D). In addition, subjects that choose listening levels that allow them to hear others speaking to them during device use had better LFPTA thresholds than device users who reported they could not hear others speak to them while using their devices (Figure 4E). Single-frequency comparisons revealed statistically reliable differences at 1, 2, 3, and 4 kHz (Figure 4F). Taken together, the evidence suggesting an effect of music player use on thresholds was limited to an effect of long-time use (> 5 years), and use of the device at higher listening levels.

Discussion

In this retrospective analysis assessing the effects of recreational noise exposure on EHF thresholds in young adults, the one source of sound exposure that was reliably related to higher thresholds was music player use. Statistically significant group differences were shown for long-term music player device users, and device users that select higher listening levels, with approximately 3–6 dB deficits detected in those user groups in this sample. The effect size reported here is within the range established by earlier literature. The largest deficits to date were measured in a study of students at Wuhan University (ages 19–23 years). In those participants, threshold deficits were approximately 6 dB at 10 kHz, and approximately 15 dB at 16 kHz, when participants who had used personal music players for greater than 5 years were compared to control subjects who did not use these devices (Peng et al., 2007). Group differences reported by others have been smaller. Deficits in the range of 2–4 dB were reported at 10–16 kHz in Brazilian secondary school students, teachers, and staff who use MP3 players regularly (defined as at least 1 hr use per day for at least one year) (Figueiredo et al., 2012). Based on these observations, it is reasonable to conclude that EHF deficits have the potential to increase with additional years of device use.

In the current study, music player listening level appeared to have a robust relationship with the observed threshold differences at EHF frequencies. While preferred listening level was not explicitly measured, subjects did report whether they used their device in noisy areas, quiet areas, or both. Most of the available data suggest that listening levels increase when devices are used in a noisy background (Hodgetts et al., 2007; Hodgetts et al., 2009; Epstein et al., 2010; McNeill et al., 2010; Muchnik et al., 2011; Portnuff et al., 2011), supporting the use of background noise levels as a rough metric for listening level. Subjects also reported whether they could hear someone speaking to them while using the device. Because all of these subjects had “normal” thresholds (i.e., at least 25 dB HL or better), ability to hear someone speaking would be strongly influenced by the volume of the device. Such data directly lead to the interpretation that listening at levels which preclude detection of environmental sound increases the risk for higher thresholds, but it should be stressed that threshold differences averaged only 3 dB at the lower frequencies (Figures 4C, 4D), while growing to 6 dB at the EHF frequencies (Figures 4E, 4F). Other studies describing thresholds at conventional test frequencies report similarly small deficits in pure-tone

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audiometric thresholds (e.g., 2–3 dB; see Meyer-Bisch, 1996; Kim et al., 2009), or no threshold deficits (Wong et al., 1990; Mostafapour et al., 1998; Kumar et al., 2009; Shah et al., 2009).

The fact that the multiple groups have measured threshold compromise at frequencies beyond 10 kHz due to long-term music player use is interesting. One possibility is that this low-dose chronic noise exposure potentiates age-like changes in the cochlea. Age-related increases in EHF thresholds are well documented (Osterhammel & Osterhammel, 1979; Schechter et al., 1986; Green et al., 1987; Stelmachowicz et al., 1989; Lee et al., 2012). The effects of aging have been attributed to four mechanisms of cochlear pathology based on data from animal models and human temporal bones. The proposed categories include sensory ARHL (hair cell loss), neural ARHL (primary ganglion cell loss), metabolic ARHL (strial atrophy) and cochlear conductive ARHL (as a consequence of stiffening of the basilar membrane), with the caveat that most cases of ARHL are of mixed origin in humans (Schuknecht, 1955; Schuknecht, 1964; Schuknecht & Gacek, 1993; Gates & Rees, 1997; Chisolm et al., 2003; Ohlemiller, 2004; Gates & Mills, 2005; Ohlemiller & Frisina, 2008; Ohlemiller, 2009). The steeply sloping pattern of high-frequency hearing loss has historically been attributed to sensory cell loss. It is clear that noise insult damages hair cells not only at the frequencies associated with the noise insult, but also at higher frequencies (i.e., the so-called ‘half-octave shift’, as well as other, higher, "unexpected" frequencies, see Davis et al., 1950; Mitchell et al., 1977; Cody & Johnstone, 1980; Cody & Johnstone, 1981; Yamashita et al., 2004; Le Prell et al., 2007). Importantly, there is increasing suggestion that some of the high-frequency hearing loss attributed to ARHL may in fact reflect the effects of noise insult in addition to age-related cell loss. Taken together, long-term music player use, and use of the device at higher listening levels, may result in harm to the high-frequency basal end of the cochlea, evident here as poorer EHF hearing.

It is important to note that age and noise can interact. Studies in mice demonstrate that exposures producing a single robust TTS early in life can result in long-term spiral ganglion degeneration and increased hearing loss over the course of the mouse’s life span, which is approximately 2 years (Kujawa & Liberman, 2006). More recent data from rodent models show rapidly decreased synaptic connections between inner hair cells and the auditory nerve dendrites associated with a single robust temporary threshold shift (TTS) following noise insult (Kujawa & Liberman, 2009; Lin et al., 2011). Multiple episodes of TTS have the potential for increasing this damage (Wang & Ren, 2012). In our sample of young adults, 6% of the subjects reported that they previously experienced a change in hearing after exposure to loud sound, and 56% reported that they had previously experienced tinnitus after loud sound (Table 1). We do not have any measures of the extent or duration of the previous TTS, and, moreover, the point at which TTS insult has the potential to result in neural change has not been identified (for detailed discussion, see Le Prell et al., 2012). Thus, the significance of this work with respect to potential synaptic trauma in young adults that use music players is unclear, but, electrophysiological tests that document the integrity of the neural population are critically needed. The small EHF deficits observed here could reflect a slowly-progressive accumulated insult triggered by multiple periods of noise stress and synaptic trauma. More importantly, it is possible that the modest change in thresholds could indicate significant auditory nerve fiber deterioration.

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Variability in thresholds at EHF frequencies, across subjects, has been noted by multiple groups (Schechter et al., 1986; Green et al., 1987; Stelmachowicz et al., 1989; Frank, 2001; Schmuziger et al., 2004). Frank (2001) has demonstrated that within-subject test-retest reliability can be just as good as at lower frequencies, and our own in-house test-retest data from a smaller number of subjects are consistent with his systematic assessment (unpublished). One possible explanation for increased variability at EHF thresholds across individuals is that inter-subject differences in noise history could contribute to deficits in EHF thresholds, in the absence of changes at conventional test frequencies. In other words, the increased variability may reflect effects of noise. Here, we tested the hypothesis that EHF thresholds in participants with a history of recreational noise exposure would be reliably worse than EHF thresholds from participants reporting less recreational noise exposure. The current analysis revealed that long-term (>5-year) music player use or use of the device at higher listening levels may result in higher thresholds at EHF frequencies.

With respect to the broader question, integrating multiple noise sources for an overall recreational noise risk metric, there was no reliable relationship between the number of reported noise sources and pure-tone-average thresholds (LFPTA, HFPTA, EHFPTA) or thresholds at individual frequencies for this sample of young adults. The potential for differences in LFPTA, HFPTA, and EHFPTA thresholds, and thresholds at individual frequencies, was specifically examined as a function of frequent bar/club attendance and concert attendance, given that the average measured sound level in bars and clubs, and at concerts, commonly reaches or exceeds 100 dBA (Cabot et al., 1979; Gunderson et al., 1997; Smith et al., 2000; Serra et al., 2005; Opperman et al., 2006; Müller et al., 2010; Williams et al., 2010). However, we found no statistically reliable differences in thresholds as a consequence of these activities. Sports events sound levels have been reported to reach or exceed 90 dBA, although the literature is not extensive (Hodgetts & Liu, 2006; Engard et al., 2010). We similarly failed to find any statistically reliable relationship between threshold and sporting event attendance. Although it has been suggested that EHF thresholds are more vulnerable to noise insult than other frequencies within the conventional 250 Hz to 8 kHz range, the current data largely fail to support this hypothesis, with the exception of music player use for long periods of time, or at high listening levels.

Because most of these exposures (concerts, bars, sports events) are recreational in nature, they are limited with respect to duration and frequency, and would not by themselves meet the definition of hazardous noise as described in the federal noise regulations (29 CFR 1910.95). These regulations, enforced by the Occupational Safety & Health Administration (OSHA), mandate the use of hearing protection devices for any worker that is exposed to sounds exceeding personal exposure limits (PEL) of 90 dBA × 8 hours per day, based on the increased probability of hearing impairment with exposures 8 hours per day, 5 days per week, over the course of a 40-year occupational career. Thus it is not surprising that the young adult college students presented here did not have significant threshold deficits as a consequence of recreational exposures. Given the well-documented increase in variability in thresholds (for populations, not individuals) at EHF frequencies, and multiple suggestions that EHF frequencies are more vulnerable to noise insult than other lower frequencies, it was reasonable to explore the potential relationship between recreational noise exposure and EHF thresholds. Although the present dataset largely failed to support the proposed

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relationship between most recreational noise sources and “pre-clinical” damage (assessed using EHF thresholds), the statistically reliable relationship between music player use factors and elevated EHF thresholds provides a cautionary note for device users regarding the potential for increasing effects with long-term use and high listening levels. The potential utility of EHF thresholds for monitoring early effects of noise cannot be excluded.

Whereas the utility of an early warning is clear, and several studies clearly support the use of EHF testing to detect subtle deficits in noise exposed populations (Ahmed et al., 2001; Biassoni et al., 2005; Serra et al., 2005; Peng et al., 2007), the literature is in fact highly mixed with respect to effects of noise at EHF frequencies. Several groups of military personnel have been tested at EHF frequencies, with no clear utility for the testing. For example, Balatsouras et al. (2005) compared thresholds in 18–21 year-old male soldiers not yet exposed to military weapons noise (n=30) with thresholds from 39 young soldiers seen after acute acoustic trauma. Deficits in noise-exposed patients were greatest at 4–8 kHz, and although they extended to 11.2 kHz, in the EHF range, there were no threshold differences from 12.5 to 20 kHz when noise-exposed soldiers were compared to soldiers not yet exposed to noise (Balatsouras et al., 2005). Kuronen et al. (2003) similarly compared conventional and EHF thresholds in Finnish Air Force Military Personnel, 19–48 years old (50 male, 1 female) to Finnish normative data and found no hearing deficits in either conventional or EHF test outcomes. They considered whether EHF tests might reveal TTS deficits after exposure to flight noise. Comparison of pre- and post-flight hearing tests indicated small (1 to 3 dB) but statistically significant TTS at both conventional and EHF frequencies, suggesting no additional benefit was obtained by adding EHF testing to the conventional test paradigm (Kuronen et al., 2003). In a study on TTS after music player use, EHF deficits did not accompany TTS measured at lower frequencies (Le Prell et al., 2012). Data from musicians are akin to those of military personnel. EHF threshold deficits (12.5 and 14 kHz) accompanied deficits at conventional test frequencies (3–8 kHz) in one group of musicians (Schmuziger et al., 2006). However, EHF threshold deficits were minimal (Axelsson & Lindgren, 1978; Axelsson et al., 1995), or not detected at all (Johnson et al., 1985; Johnson et al., 1986), in other groups of musicians. When TTS after music rehearsal was evaluated, TTS was detected at frequencies at and below 8 kHz but not at or above 9 kHz (Schmuziger et al., 2007). Musicians, military personnel, and music player users will have significantly different exposure to noise, with respect to frequency and duration of exposure, sound levels, as well spectral content, and kurtotic distribution. It may ultimately prove to be the case that some patterns of exposure are more likely to result in slowly progressive changes in the basal cochlea than other patterns of exposure, a finding that would explain the diverse outcomes regarding the utility of EHF monitoring.

Summary and Conclusions

Despite the potential for “early warning” benefits, the literature is mixed with respect to the utility of EHF thresholds for identifying early effects of noise. The present data clearly suggest that music player use can drive threshold changes during EHF tests. Howevr, the present data provide no compelling evidence that most normal recreational noise exposure (including periodic concert attendance, bar/club attendance, sporting event attendance, or combinations of the above) induce EHF threshold changes in healthy young adult

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populations. Longitudinal data are critically needed to determine the extent to which EHF deficits are, or are not, followed by changes in conventional audiometry.

Although the utility of EHF threshold for monitoring “pre-clinical” changes in auditory function remains unclear, we encourage clinicians to consider routine testing at EHF frequencies. An effort to detect the earliest changes in hearing may offer an opportunity to provide information about the possible consequences of continued risky listening behavior, particularly when audiologic history reveals a history of noise exposure. RETSPLs are a reliable reference against which hearing among young adults can be compared. However, as older populations are compared to the RETSPL normative hearing levels, increasing divergence is expected as age-related increases in EHF thresholds are well documented (Osterhammel & Osterhammel, 1979; Schechter et al., 1986; Green et al., 1987; Stelmachowicz et al., 1989; Lee et al., 2012).

Serial monitoring at EHF frequencies has been readily possible for new patients entering therapeutic treatment with ototoxic drugs. Baseline testing is implemented prior to the first drug administration, and EHF monitoring provides physicians with valuable information regarding potential permanent hearing loss. EHF monitoring is routinely used to help guide drug titration to preserve hearing, or if the drug therapy cannot be modified, to guide the onset of rehabilitation services (see, for example, Fausti et al., 1999; Vaughan et al., 2002; Knight et al., 2007; Konrad-Martin et al., 2010; Jacobs et al., 2012). If emerging noise-induced deficits at EHF thresholds could be similarly routinely identified, this may provide parallel opportunities for intervention. With respect to hearing conservation programs, employers may be able to choose to move workers to less noisy workstations, or implement engineering controls. On an individual level, employees might begin use of or be refit with hearing protection devices (HPDs), and receive counseling about noise outside the workplace. Finally, if EHF deficits could be routinely identified in adolescents, at-risk individuals could perhaps be encouraged to attend educational programs such as Dangerous Decibels (Griest et al., 2007), Sound Sense™ (Neufeld et al., 2011), or other hearing conservation educational programs (Lass et al., 1986; Lukes & Johnson, 1998). Although there is not yet a significant database documenting long-term change in adolescent listening behaviors as a function of such educational outreach programs, early efforts to document long-term improvements are encouraging.

Acknowledgments

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Abbreviations

ANSI	American National Standards Institute
EHF	extended high frequency

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EHFPTA	extended high-frequency pure-tone average/average threshold at 10, 12, 14, and 16 kHz
dB HL	decibels hearing level
dB SPL	decibels sound pressure level
HFPTA	high-frequency pure-tone average/average threshold at 3, 4, and 6 kHz
Hz	Hertz
kHz	kilohertz
LFPTA	low-frequency pure-tone average/average threshold at 0.5, 1, and 2 kHz
NIHL	noise-induced hearing loss
PTA	pure-tone average
RETSPL	Reference Equivalent Threshold Sound Pressure Level
TTS	temporary threshold shift

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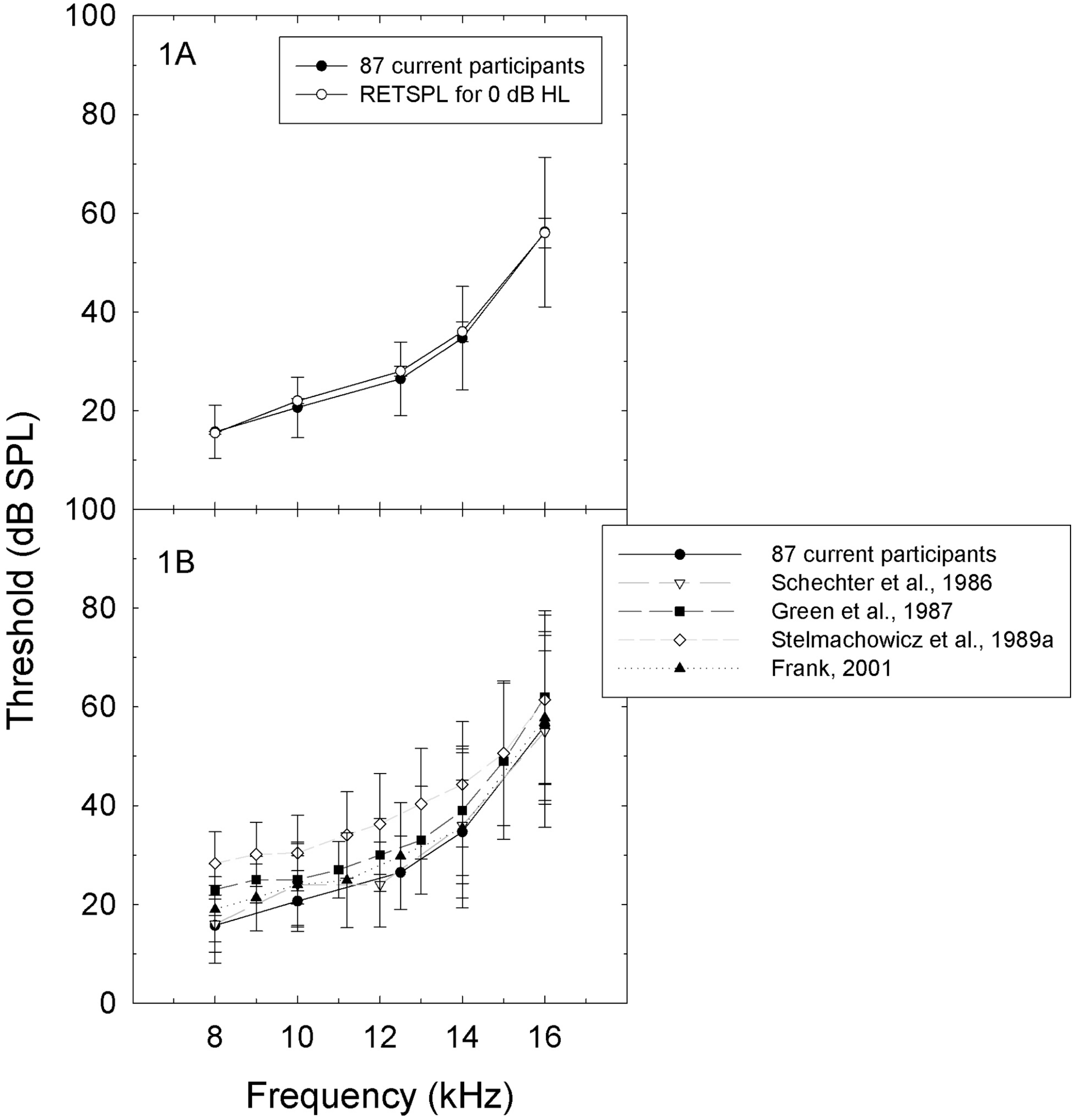

Figure 1.

A. Average EHF thresholds measured from current subjects at frequencies from 8–16 kHz closely matched the RETSPL sound levels identified as normal hearing threshold level in ANSI S3.6 1996 Annex C. Figure 1B. EHF thresholds measured from current subjects tested at frequencies from 8–16 kHz were consistent with those reported by Schechter et al. (1986; mean and SD for subjects ages 16–20 years old, from their Tables I and II), Green et al. (1987; mean and SD for 37 subjects ages 18–26, from their Table II), Stelmachowicz et al.

(1989; mean and SD for 160 subjects ages 10–19, from their Table I), and Frank (2001; mean and SD for 100 subjects ages 18–25, from his Table I).

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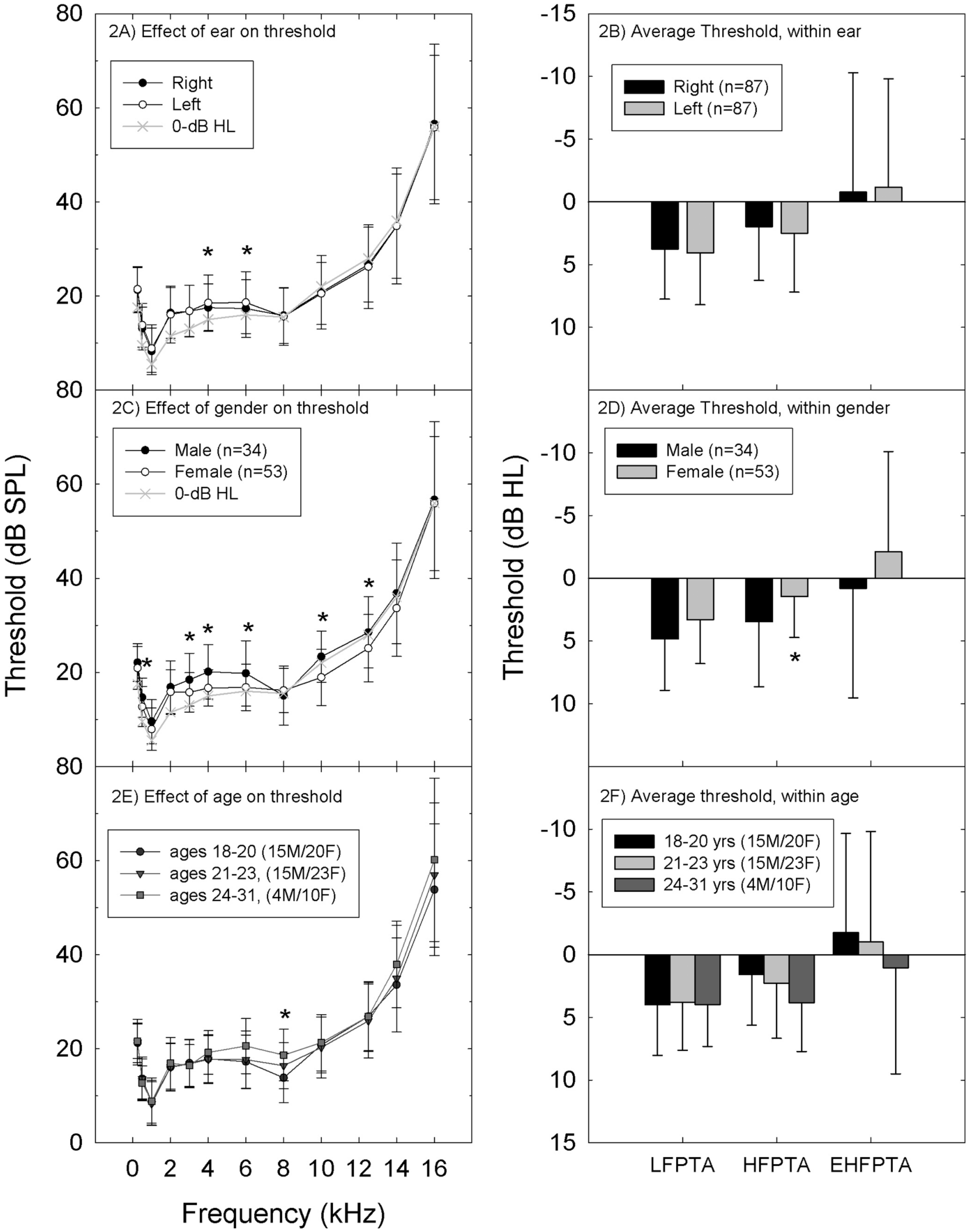

Figure 2.

Factors that may influence thresholds include ear (2A,2B), gender, (2C,2D), and age (2D, 2E). Ear. For these 87 subjects, small but statistically reliable differences were detected for right versus left comparisons at 4 and 6 kHz (2A), with no differences in pure-tone average threshold at 0.5, 1 and 2 kHz (LFPTA), 3, 4, and 6 kHz (HFPTA), or 10, 12, 14, and 16 kHz (EHFPTA) (2B). The thresholds defined as “0-dB HL” in the ANSI standard are plotted for comparisons purposes in Figure 2A, and pure-tone average thresholds are plotted using the dB HL convention (2B). Gender. Small but systematic differences were observed when

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males were compared to females, with males having poorer hearing at 0.5, 3, 4, 6, 10, and 12 kHz (2C). The effect of gender was observed for HFPTA comparisons, but not LFPTA or EHFPTA (2D). Age. There was a small but statistically reliable elevation in threshold at 8 kHz as a function of age (2E). Deficits did not extend to PTA comparisons (2F).

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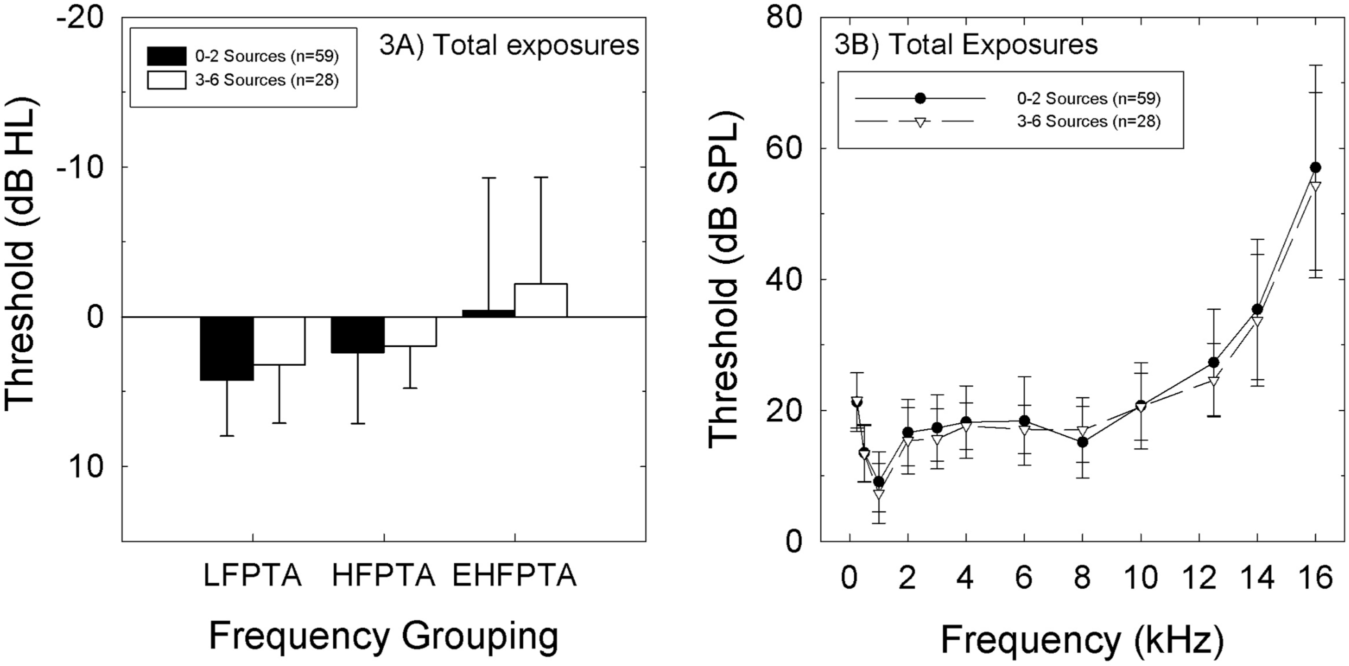

Figure 3.

A. There was no relationship between pure-tone-average threshold and number of noise sources reported by the subjects. Figure 3B. There was no relationship between thresholds at individual EHF frequencies and number of noises sources reported by the subjects.

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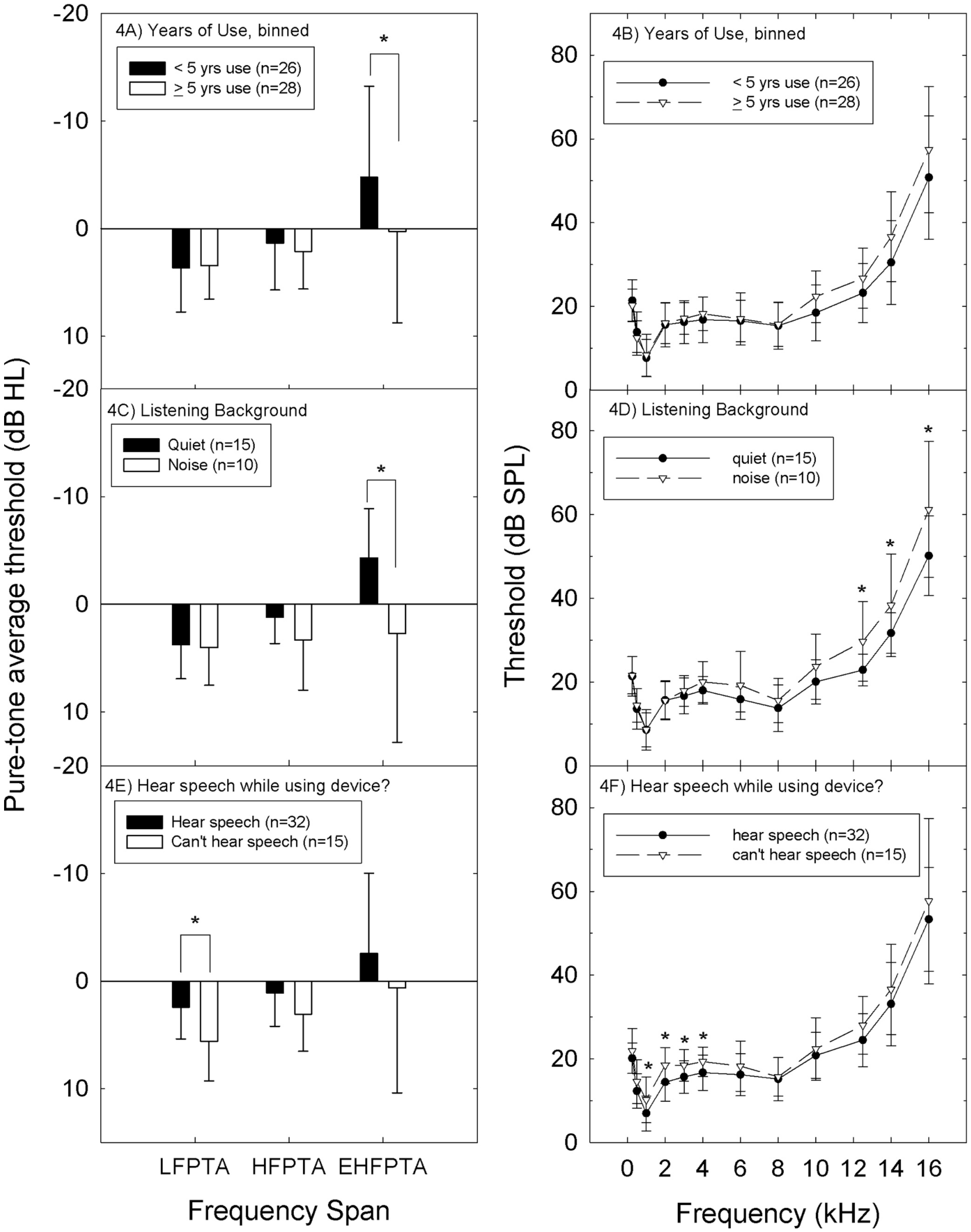

Figure 4.

A. There was a statistically reliable relationship between PTA threshold and long-term use of a music player device, defined as greater than 5-years of device use, using the EHFPTA metric (average threshold at 10, 12, 14, and 16 kHz). Figure 4B. Single frequency comparisons revealed statistically reliable differences at 10 and 14 kHz. Group differences at 12 and 16 kHz were not statistically reliable at the $\alpha=0.05$ level. Figure 4C. Average PTA thresholds at EHF frequencies were reliably worse in those subjects that used their devices in noisy backgrounds ($p<0.05$). Figure 4D. Single frequency comparisons revealed

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statistically reliable differences at 12, 14, and 16 kHz. Figure 4E. Average PTA threshold for low frequencies (0.5, 1, 2 kHz) was reliably worse in those subjects that could not hear others speaking to them ($p<0.05$) with a similar trend observed for conventional high frequencies (3, 4, and 6 kHz: HFPTA $p=0.055$). Figure 4F. Single-frequency comparisons revealed statistically reliable differences at 1, 2, 3 and 4 kHz.

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Table 1

General health/hearing health characteristics.

		Male **n=34 (39.1%)**	**Female** **n=53 (69.1%)**	**All Subjects** **n=87**
Age		21.4 yrs±2.4yrs Range=18–29 yrs	21.7 yrs±2.6yrs Range=18–29 yrs	21.6 yrs±2.5yrs Range=18–29 yrs
Height (feet)		5.8 ft ±0.3 ft Range=5.2–6.4 ft	5.4 ft ±0.3 ft Range=4.9–6 ft	5.5 ft ±0.3 ft Range=4.9–6.4 ft
Weight (pounds)		159 lbs±26 lbs Range=120–250	140 lbs±33 lbs Range=85–255	147 lbs±32 lbs Range=85–255
Tobacco user (% yes)		4 (12%)	1 (2%)	5 (6%)
Cigarettes		2 (6%) (plus 1 former)	1 (2%)	3 (3%)
Cigars		1 (3%)	0	1 (1%)
Pipe		1 (3%)	0	1 (1%)
Chew		0	0	0
Alcohol use (% yes)		21 (62%)	25 (47%)	46 (53%)
0 drinks/week		13 (38%)	28 (53%)	41 (47%)
1–5 drinks/week		17 (50%)	19 (36%)	36 (41%)
6–10 drinks/week		4 (12%)	6 (11%)	10 (12%)
Hearing aids (% yes)		0	0	0
Ear pain/Ear ache (% yes, previously)		3 (9%)	6 (11%)	9 (10%)
Ear drainage (% yes, previously)		1 (3%)	0	1 (1%)
Ear infections (% yes, previously)		8 (24%)	12 (23%)	20 (23%)
Ringing in ears (% yes-currently, % yes-previously)		2 (6%) 6 (18%)	0 8 (15%)	2 (2%, yes-currently) 14 (16%, yes-previously)
Balance Disturbance (% yes, previously)		1 (3%)	2 (4%)	3 (3%)
Seizures (% yes, previously)		1 (3%)	0	1 (1%)
Freq severe headaches (% yes, previously)		2 (6%)	2 (4%)	4 (5%)
Stroke (% yes, previously)		0	0	0
Fainting (% yes, previously)		0	4 (8%)	4 (5%)
Disorientation (% yes, previously)		1 (3%)	0	1 (1%)
Parent or Sibling with hearing loss? (% yes)		2 (6%)	10 (19%)	12 (14%)
Have you ever had an ear infection? (% yes)		18 (53%)	25 (47%)	43 (49%); None were within past 3 months
Have you ever had hearing loss? (% yes)		1 (3%)	4 (8%)	5 (6%); all 5 reported “only after loud sound”
Are you overly sensitive to loud sound? (% yes)		1 (3%)	1 (2%)	2 (2%)
Have you ever heard “ringing” in your ears after noise? (% yes)		21 (62%)	28 (53%)	49 (56%)
If yes, does this happen:	Always	2/21=10%	1/28=36%	3/49=6%
	Often	4/21=19%	4/28=24%	8/49=16%
	Occasionally	4/21=19%	9/28=32%	13/49=27%
	Rarely	11/21=52%	14/28=50%	25/49=51%

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		Male **n=34 (39.1%)**	**Female** **n=53 (69.1%)**	**All Subjects** **n=87**
	in absence of noise? (% yes)	8/21=38%	7/28=25%	15/49=31%

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Table 2

Noise history.

		Male **n=34 (39.1%)**	**Female** **n=53 (69.1%)**	**All Subjects** **n=87**
Specific Noise Sources Surveyed				
Bar/Club		11 (32%)	25 (47%)	36 (41%)
Hunting/Shooting		1 (3%)	0 (0%)	1 (1%)
Sports		10 (29%)	8 (15%)	18 (21%)
Concert		7 (21%)	11 (21%)	18 (21%)
Music Rehearsal		5 (15%)	0 (0%)	5 (6%)
Music Player		18 (53%)	31 (58%)	49 (56%)
Music in Vehicle		13 (38%)	16 (30%)	29 (33%)
Workplace		3 (9%)	1 (2%)	4 (5%)
Total number of frequent or monthly noise sources reported		2.0±1.6 Range=0–6	1.8±1.2 Range=0–4	1.9±1.4 Range=0–6
Any Unprotected Impulse Noise (% yes)		13 (38%)	19 (36%)	32 (37%)
Use a music player?		31 (91%)	47 (89%)	78 (90%)
54 subjects (21M, 33F) subjects were asked more detailed information. Of these, 46 subjects used music players (18M, 28F). Their responses are shown here.	Hours per day	<1: 9/18=50% 1–2: 6/18=33% 3–5: 3/18=17% 5–8: 0/18 >8: 0/18	<1: 13/28=46% 1–2: 12/28=43% 3–5: 1/28=4% 5–8: 2/28=7% >8: 0/28	<1: 22/46=48% 1–2: 18/46=39% 3–5: 4/46=9% 5–8: 2/46=4% >8: 0/46
	Days per week	<1: 3/18=17% 1–2: 2/18=11% 3–5: 7/18=39% 5–7: 6/18=33%	<1: 3/28=11% 1–2: 5/28=18% 3–5: 17/28=61% 5–7: 3/28=11%	<1: 6/46=13% 1–2: 7/46=15% 3–5: 24/46=52% 5–7: 9/46=20%
	Years of use	<1: 1/18=6% 1–2: 1/18=6% 3–5: 4/18=22% 5–8: 5/18=28% >8: 7/18=39%	<1: 1/28=4% 1–2: 0/28 3–5: 11/28=39% 5–8: 6/28=21% >8: 10/28=36%	<1: 2/46=4% 1–2: 1/46=2% 3–5: 15/46=33% 5–8: 11/46=24% >8: 17/46=37%
	Type of earphones	Earbuds: 11/18=61% Inserts: 5/18=28% Headphones: 3/18=17%	Earbuds: 21/28=75% Inserts: 5/28=18% Headphones: 3/28=11% Did not respond: 1/28=4%	Earbuds: 32/45=71% Inserts: 10/45=22% Headphones: 6/45=13%
	Common listening environment?	Noise: 6/18=33% Quiet: 7/18=39% Both: 4/18=22% Other: 1/18=6% (outdoors)	Noise: 4/28=14% Quiet: 8/28=29% Both: 14/28=50% Other: 2/28=7% (outdoors, car)	Noise: 10/46=22% Quiet: 15/46=33% Both: 17/46=37% Other: 3/46=7% (outdoors, in car)
	Hear someone speaking to you? (% yes)	14/18=78%	18/28=64%	32/46=70%
Play a musical instrument?		10/34=29%	6/53=11%	16/87=18%
54 subjects (21M, 33F) subjects were asked more detailed information. Of these, 13 subjects played musical instruments (7M, 27F). Their responses are shown here.	Hours per day, solo	<1: 1/7=14% 1–4: 4/7=57% 5–10: 2/7=29% >10: 0/7	<1: 2/6=33% 1–4: 2/6=33% 5–10: 1/6=17% >10: 1/6=17%	<1: 3/13=23% 1–4: 6/13=46% 5–10: 3/13=23% >10: 1/13=8%
	Hours per day, group rehearsal	<1: 3/7=43% 1–4: 3/7=43% 5–10: 1/7=14% >10: 0/7	<1: 3/6=50% 1–4: 2/6=33% 5–10: 0/6 >10: 1/6=17%	<1: 6/13=46% 1–4: 5/13=38% 5–10: 1/13=8% >10: 1/13=8%

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		Male **n=34 (39.1%)**	**Female** **n=53 (69.1%)**	**All Subjects** **n=87**
	Years played	1–4: 2/7=29% 5–10: 3/7=43% >10: 2/7=29%	1–4: 1/6=17% 5–10: 5/6=83% >10: 0/13	1–4: 3/13=23% 5–10: 8/13=62% >10: 2/13=15%
	Type of instrument	Brass: 1/7=14% Woodwind: 3/7=43% String: 6/7=86% Percussion: 4/7=57% Other: 1/7=14% (voice)	Brass: 1/6=17% Woodwind: 1/6=17% String: 3/6=50% Percussion: 1/6=17% Other: 0	Brass: 2/13=15% Woodwind: 4/13=31% String: 9/13=69% Percussion: 5/13=38% Other: 1/13=8% (voice)