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Unsafe at any sound: hearing loss and tinnitus in personal audio system users

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Personal audio systems (PAS) use is a major risk factor for noise-induced hearing loss (NIHL). PAS include a content device and earbuds or headphones for listening to personal audio without disturbing others. PAS are inherently unsafe because their design exposes users to high sound pressure levels. PAS users are at about 4-times greater risk of developing NIHL than non-users, with hearing loss reported in users as young as 9. The greatest risk is for personal listening >1 hour daily > 50% volume for >5 years. Nearly 50% of PAS users aged 12-35 listen at volume settings >50%, putting 1.1 billion young people worldwide at risk of auditory damage. PAS users have a higher risk of tinnitus and hidden hearing loss than non-users. Children and teenagers are at higher risk than adults from noise exposure during auditory system developmental periods. Hearing loss has a greater impact on young people than older adults because good hearing is vital for communication, socialization, education, and future vocational success. A harmonized global manufacturing standard is needed, specifying PAS sound output limits based on the non-occupational 70 dBA daily average noise exposure limit. Without regulated PAS sound limits, preventable NIHL and tinnitus will continue to increase.

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Introduction

In 1965, pioneering consumer activist Ralph Nader published *Unsafe at Any Speed: The Designed-In Dangers of the American Automobile*.[1] This book brought attention to the fact that automobiles were inherently unsafe to drive because of their design, including inadequate brakes, non-collapsible steering columns, and poor crash protection. Personal audio systems (PAS), also called personal music players or personal listening devices, are used for listening to audio without disturbing others. PAS include content source devices such as MP3 players or smartphones used with transducers such as earbuds or headphones. We have reviewed scientific evidence demonstrating that PAS are inherently unsafe because of their design, delivering high intensity sound directly to the ears. Like automobiles in the pre-Nader era, in theory PAS can be used safely, but sound exposures put PAS users at great risk of noise-induced auditory damage. Like automobiles, risk can't be eliminated completely, but PAS can be made safer to use.

Noise is unwanted and/or harmful sound.[2] Although people may enjoy using PAS, even wanted sound can damage auditory health when sound energy is intense enough.[3] Auditory risk is highest for cumulative or repeated episodes of unsafe sound exposure over a person's lifetime, even when interspersed with periods of quiet. PAS use combined with additional environmental, entertainment, and/or occupational noise exposure increases individual auditory risk. The World Health Organization (WHO) estimates that 1.1 billion young people worldwide, nearly 50% of those aged 12-35, are at risk of noise-induced hearing loss (NIHL) because of recreational noise exposure, including PAS use.[4] This includes approximately 50 million Americans[5] and 6 million Canadians.[6] Therefore, this paper focuses on adverse effects of PAS on the young, although older PAS users are not immune to auditory damage.

Hearing loss is an invisible disability that impacts multiple aspects of daily life. Early onset NIHL causes greater consequences because individuals are affected for the rest of their lives. Early hearing loss, even slight-mild,[7] can affect speech and language development, communication, interpersonal relationships, social development, self-esteem and mental health, cognitive health, education and academic success, and future employment and economic success.[4,8,9] In later life, mild hearing loss increases dementia risk 2 times, moderate hearing loss 3 times, and severe hearing loss 5 times.[10]

PAS use begins in childhood, as early as age 3.[11] Among a sample of >10,000 Canadian children and teenagers, prevalence of PAS use was >29% at age 6, 59% at age 9, 80% at age 12, and 85-95% from ages 12-19.[12] Peripheral and central auditory system development continues both anatomically and functionally from birth into the late teenage years.[13] Children and teenagers are likely at a higher auditory risk from noise exposure during auditory system development already complete in adults.[14,15] In addition, hearing sensitivity and acuity in the standard to extended high frequencies contribute to fine frequency resolution, speech intelligibility, sound localization, and cognitive function.[16,17,18]

Noise-induced auditory impairments

There are sizable differences in noise susceptibility among individuals ranging from "tender" to "tough" ears.[19] Besides young age, factors that may cause higher noise sensitivity include pre-existing hearing loss or tinnitus, gender, skin pigmentation, and certain diseases.[18,20] Males are more susceptible than females because they express lower levels of the otoprotective hormone estrogen. People with fair skin and eyes are more susceptible than people with dark skin and eyes who have more otoprotective melanin. Diseases that put people at higher susceptibility from noise exposure include high blood pressure or cardiovascular disease, diabetes, Bell's palsy, and auditory system genetic mutations. Depending on the individual, similar exposures could cause different amounts of auditory damage.

What is normal hearing? Normal hearing allows individuals to understand speech in quiet and noisy environments.[4] People under age 40 demonstrate mean hearing thresholds within the normal hearing range, -10 to 15 decibel hearing level (dB HL),[7] on standard audiometry testing frequencies from 250 hertz (Hz) to 8 kilohertz (kHz) and on extended high frequency (EHF) audiometry testing from 9 kHz to

16 kHz.[21,22] Mean hearing thresholds in noise-isolated populations show only slight-mild high frequency hearing loss by age 70, disputing the belief that hearing loss is part of physiological aging.[23,24,25]

Significant noise-induced auditory damage precedes clinically detectable auditory changes. In 2006, Kujawa and Liberman reported that noise damage in animal models begins with rapid loss of synaptic connections between cochlear outer hair cells and the auditory nerves, now known as cochlear synaptopathy, not with hair cell loss as previously thought.[26,27] Progressive post-exposure auditory nerve degeneration follows cochlear synaptopathy,[28,29] resulting in auditory neuropathy[30] or hearing impairment where the brain does not process sound accurately, e.g. frequency and/or intensity distortion. Dobie and Humes think it is premature to conclude that permissible American occupational noise exposures could cause cochlear synaptopathy,[31] but Kujawa and Liberman argue that cochlear synaptopathy is common in humans at noise exposures frequently encountered in everyday life.[32,33]

Tinnitus and hyperacusis are associated with noise exposure.[4,34] Those who suffer from these conditions often report that a single exposure caused their symptoms.[35] Tinnitus, which is the perception of sound in the absence of an external sound source, has a negative impact on quality of life, including concentration problems, insomnia, anxiety, depression, social withdrawal, higher risk of accidents, and suicidal ideation.[18,36,37,38] Tinnitus may precede NIHL[39] or occur after hearing loss has developed.[40] Hyperacusis is painful decreased sound tolerance, which is associated with sound avoidance, social isolation, anxiety, depression, and suicidal ideation.[18] Hyperacusis can be a manifestation of hidden hearing loss (HHL).[33]

HHL develops before NIHL.[41] HHL is called "hidden" because the auditory impairments causing it are not found on standard audiometry. It typically manifests itself clinically by speech-in-noise (SIN) hearing loss. This is a common condition, affecting approximately 20-40% of middle-age adults.[42] Patients complain that they have difficulty following one conversation among many in noisy environments, such as in meetings or restaurants, but their hearing thresholds are within the normal range. In addition to SIN hearing loss and hyperacusis, HHL indicators include impaired cochlear function on otoacoustic emissions testing, and EHF audiometry deficits, typically first developing in the 14-16 kHz range.[30]

Temporary threshold shift (TTS) is a precursor to permanent threshold shift or NIHL. TTS is a temporary increase in the threshold of audibility for an ear caused by exposure to high-intensity acoustic stimuli,[43] manifested clinically by a temporary muffling of sound perception. TTS recovers over time to pre-exposure status. Some exposed individuals may also experience temporary tinnitus or other auditory symptoms. Cumulative episodes of TTS cause greater TTS with subsequent exposures and increased risk of developing permanent tinnitus and NIHL.[44] Recovery may occur within minutes, hours, or days, up to 3 weeks post-exposure, when any remaining threshold shift is considered permanent. TTS has lasting auditory system effects and is not a benign side effect of noise or music exposure.[45]

NIHL is a permanent sensorineural loss that typically first develops in the 3-6 kHz high frequency speech range, often with an early 4 kHz notched pattern.[46,47] The loss is bilaterally symmetrical under free field sound exposure conditions. SIN hearing loss is typically worse than expected from the audiogram because of auditory neuropathy.[30] Early noise exposure with or without NIHL is associated with worsening hearing thresholds or greater NIHL in future with repeated exposures.[4,26]

Noise exposure and auditory risk relationships

Noise exposure and auditory risk relationships are largely based on occupational hearing loss research from the 1930s-1960s in unprotected noise-exposed workers age 18-65, research no longer ethically or legally feasible. There are no similar studies of noise and auditory risk relationships for children <18 or other noise-sensitive populations. The occupational noise exposure studies helped establish noise risk relationships for TTS and NIHL based on significant threshold shifts at limited pure tone frequencies on standard audiometry. Occupational risk estimates probably underestimate auditory risk because more sensitive indicators of early noise damage such as EHF audiometry and SIN testing were not used, and the presence or absence of tinnitus and hyperacusis were not assessed.

Noise may damage the audiovestibular system responsible for maintaining balance and spatial orientation, but consideration of this risk is beyond the scope of this paper.[3] For auditory risk, the decibel scale used to measure sound intensity is logarithmic, so slight changes in numeric value reflect sizable intensity differences. For example, sound intensity increases 10 times for 10 dB, 100 times for 20 dB, and 1,000 times for 30 dB differences.[48] Sound measurements can be adjusted. A-weighting adjusts dB measurements to approximate the human auditory response to sound, and is generally used for NIHL risk assessments, but C-weighting may better measure music's low frequency bass sound energy.[49]

Time-weighted average (TWA) exposures are used for occupational noise risk estimates, based on sound energy equivalent to an 8-h daily average.[43] The equal energy hypothesis states that sound energy and exposure time can be traded off, under the assumption that equal energy sound exposure will produce similar hearing impairment. Sound energy is considered equal when intensity doubles (+3 dB) and the exposure time is halved. However, the response of the auditory system to sound energy is nonlinear, and impulsive, intermittent, and high level noise exposure may cause greater auditory damage than that predicted by the equal energy hypothesis.[50] In addition, auditory systems do not process sound energy as a TWA. Total sound intensity travels through the auditory system instantaneously in real time. Flamme et al. stated that 75-78 dBA is the auditory injury threshold where exposure causes noise-induced threshold shift regardless of listening time.[14,51,52,53]

Occupational NIHL risk is based on cumulative daily 8-h TWA exposure over a working career, 5 days/week, 240 days/year, for 40 years, and assumes that the individual spends the other 16 hours a day and weekends in quieter environments <60 dBA.[54] In contrast, non-occupational NIHL risk is based on cumulative daily 24-h average exposure over the course of a lifetime, 7 days/week, 365 days/year, for close to 80 years in most industrialized countries. Quiet intervals may permit some recovery from adverse effects of noise exposure. Kryter concluded that the Effective Quiet Level or maximum sound pressure level (SPL) that allows the ear to recover from TTS is as low as 55 dBA.[55] Many PAS users *never* experience 16 consecutive quiet hours in a day. Applying occupational 8-h TWA noise exposure limits to the public underestimates auditory risk.[56]

Specific SPLs affect human health and function. Two are relevant to this discussion. Occupational noise exposure of ≥80 dBA TWA is associated with excess risk of material hearing impairment compared to unexposed populations. Excess risk in healthy adults is 1% at 80 dBA, 8% at 85 dBA, and 25% at 90 dBA TWA.[43]. Material hearing impairment is defined as hearing thresholds >25 dB HL pure tone average at 1-2-3-4 kHz for the median of the adult population. This impairment will cause speech intelligibility problems, especially in noisy environments.[4] In addition, occupational and non-occupational studies show that SPL ≥80 dBA may cause TTS.[19] Studies have identified TTS risk in humans from 80 dBA exposure for 30 minutes,[25] and as low as 76 dBA for 8 hours of broadband noise and 65 dBA for 4 hours of octave-band noise centered at 4 kHz, which is usually the most sensitive frequency for noise damage.[57]

The L_{EQ} or equivalent continuous average SPL is considered the best metric for average noise measurements.[39] The evidence-based non-occupational noise exposure to prevent NIHL, for the median of the adult population, is 70 dBA daily average based on a 24-h time period (L_{EQ24h}).[58,59,60] Common total daily non-occupational sound exposures now regularly exceed 70 dBA.[61] The higher the average daily sound exposure, the greater the auditory risk. The 70 dBA L_{EQ24h} daily average exposure is predicted to result in similar NIHL risk as an equal energy TWA of 8-h at 75 dBA,[58] 4-h at 78 dBA, 2-h at 81 dBA, 1-h at 84 dBA, 30-min at 87 dBA, 15-min at 91 dBA, 7.5-min at 94 dBA, <4-min at 97 dBA, and <2-min at 100 dBA. However, equal energy does not necessarily mean equal auditory safety for non-occupational sound exposures. The effects of music exposure on hearing may not follow the equal energy hypothesis. Studies have found that compared to industrial noise exposure, equal amounts of sound energy from music result in different auditory impairments, including longer recovery time from TTS.[62, 63]

Most people, including some experts in acoustics, audiology, and otolaryngology, are unaware of the risk that lower noise levels pose for auditory health. Persistent noise exposure of 50-80 dB SPL may cause maladaptive central auditory system changes during auditory system development and in adulthood.[14,57] Although the precise amount of noise exposure sufficient to cause cochlear synaptopathy in humans has not yet been established,[32] it may occur at SPLs of 67-83 dBA.[57]

Personal audio system sound output

PAS are designed to deliver high intensity sound output directly to the ears, which may pose a greater risk to children than adults. According to Boyle's Law, pressure and volume are inversely proportional. Therefore, the same PAS sound pressure output travelling down a child's smaller volume ear canal may reach the tympanic membrane at greater intensity than in an adult with larger volume ear canals.[64] PAS manufacturers may include built-in volume limits, parental controls, or safer listening features, and devices usually have 2 listening modes which typically default to the highest sound exposure option.[65,66]

For decades, PAS have produced maximum sound outputs up to 126-128 dBA.[3,67] With current digital technologies, PAS users can enjoy excellent sound quality even at maximum output, without the static and distortion of earlier analog PAS technologies. Smartphones commonly used for personal listening produce minimum sound outputs of 84-92 dBA, which can cause TTS[68] and eventual NIHL with repeated exposure. Therefore, depending on the device, PAS can be unsafe at almost any user listening volume.

Williams and Purnell demonstrated that different PAS produce different sound exposures at the same volume setting.[69] Device sound output may vary up to 6.6 dB, and transducer sound output up to 8.6 dB, depending on the manufacturers. PAS sound output is also variable because of factors including different electrical sensitivities among transducers. Between-PAS sound exposure differences vary up to 40 dB at higher volume settings. For example, at 80% volume, PAS user exposure may range from 76 dBA to 94 dBA L_{EQ} depending on their device and earbud or headphone combination.

People using stock earbuds with poor quality seal against the ear and inadequate noise isolation often listen at higher sound levels in noisy environments than people using headphones, deeper insertion isolator style earbuds, or transducers with noise reduction or isolation technology.[70] PAS headphones with an 85 dB volume limit are available,[71] often falsely advertised as safe for children's hearing.[72]

PAS volume settings of 50% to 60% correspond to approximately 70 dBA to 80 dBA mean SPL,[4,73] although as discussed, sound output can vary depending on the device and transducer combination. Personal listening >50% volume could exceed the 70 dBA-NIHL noise limit. PAS use <50% of maximum volume is less likely to cause NIHL regardless of listening time or device and transducer combination.[74]

Personal audio system user listening levels

People use PAS during many activities, including studying, working, performing household chores, exercising, commuting, and sleeping.[70] Systematic reviews have identified the greatest auditory risk for PAS use >1 hour daily >50% volume for at least 1 year.[75,76] PAS users worldwide report listening up to 12 hours daily,[3] while in the USA, average users listen 4.5 hours daily.[77] Regular PAS use is most common in young people. Approximately 27% of 9-year-olds[78] and 40% of 9-11-year-olds[79] use PAS daily or several times a week. PAS are used by up to 95% of Canadian 12-19-year-olds[12] and 98% of young adults worldwide.[60] In teenagers, 21% use PAS while sleeping,[80] which increases total daily sound exposure.

Young people commonly use PAS at >50% volume setting. A Canadian study found the prevalence of PAS use ≥75% volume was 13.1% under age 12, 44.2% age 12-19, 30.3% age 20-39, 11.9% age 40-59, and 4.2% age 60-79.[12] Over 36% of college age PAS users report sometimes listening at maximum volume.[68] Personal listening volume setting is typically related to individual preferences, music frequency characteristics, and environmental noise interference.[70] Common reasons to turn up the volume include improving the signal-to-noise ratio, (e.g. to overcome ambient noise while taking public transit), exercising, singing along, or playing a favorite song.

Using NIOSH criteria, studies on teenagers and young adults in 10 countries predicted about 1 in 3 PAS users are at risk of NIHL with exposure >80 dBA.[76] As noted previously, occupational noise exposure limits underestimate risk of auditory damage. About 30% of teenagers listen >80 dBA and 10% between 90-100 dBA.[80] In PAS users age 16-69, 90% are at risk of NIHL from average noise exceeding 70 dBA with sound exposure from PAS and stereos being the primary contributing noise sources for 88% of people.[81] Under typical listening conditions, average PAS sound output exceeds the 70 dBA-NIHL noise limit. Average noise exposures during PAS use in different situations are provided below in Table 1.

Table 1: Average noise exposures during personal audio system use*

Personal audio system use	**Average noise exposure**	**Reference**
Mean preferred listening level	68-86 dBA	Basner et al. [3]
Typical volume range	75-105 dBA	WHO [4]
Estimated listener sound levels	79-125 dBA	Keith et al. [67]
Ambient quiet	79.2-82 dBA	Muchnik et al. [82], Friesen & Papadopoulos [83]
Ambient noise	89 dBA	Muchnik et al. [82]
Urban environments	94.1 dBA	Fligor et al. [84]

*Adapted from reference 61.

Personal audio system user auditory impairments

Although other etiologies can never be completely ruled out, people are thought to have noise-induced auditory damage when they have a history of harmful sound exposure plus characteristic sensorineural[7] auditory findings. It is difficult to pool published data about PAS user auditory impairments because of inconsistent age ranges, methodologies, noise criteria, and auditory impairment definitions used. Most studies have investigated NIHL and tinnitus as auditory risk indicators. Some studies have used less sensitive occupational hearing impairment criteria for analysis, which are not appropriate for non-occupational populations, including use of an 85 dBA noise criteria and >25 dB HL NIHL threshold criteria. As a result, PAS use and auditory risk relationships were likely underestimated.

Many published studies of PAS users age 12 and older show auditory impairments characteristic of noise-induced damage.[3,70,75,76,79,80,85] Studies demonstrate that HHL is associated with <5 years PAS use, (i.e., impaired otoacoustic emissions and EHF hearing loss), NIHL is associated with >5 years PAS exposure, with PAS users at about 4 times higher risk of NIHL than non-users.[76] In 18-35-year-olds with a history of high volume personal listening, approximately 75% reported tinnitus, 40% reported worsening hearing over time, and 20% reported SIN hearing loss in social situations including family dinners.[70]
Tinnitus incidence of about 28% in PAS users is significantly higher than about 8% in non-users.[3] Up to 69% of children, teenagers, and young adults who listen to music with PAS report noise-induced auditory symptoms including tinnitus.[79] PAS users who listen at least 3 hours at a time may be at higher risk of tinnitus.[80] PAS use has tinnitus risk similar to music exposure at concerts and pubs or clubs.[86]

Auditory impairments found in younger PAS users include high-frequency hearing loss or audiometric notches in 9-11-year-olds.[78,79] A study of over 6,500 Australian elementary school children found a 2 times higher risk of hearing loss in PAS users than non-users.[87] Tinnitus is a possible early indicator of NIHL in 11-12-year-old PAS users, with average listening volumes of approximately 50%.[88] Further study of risk relationships between PAS use and noise-induced auditory damage in children is needed.

Discussion

The WHO estimates that 1.1 billion young people worldwide are at risk of NIHL, including from PAS use.[4] The global costs of hearing loss are estimated at $980 billion annually. Prevention of disease or disorder is almost always more cost effective than treatment or rehabilitation.[89] Noise-damaged human ears cannot repair themselves. NIHL, tinnitus, and hyperacusis are currently incurable. Any cure for hearing loss must not only regenerate cochlear hair cells but must also repair cochlear synapses and auditory nerves to restore sound transmission to the brain.[18] Treatment for NIHL includes hearing aids, coping and lifestyle counseling, and psychiatric services.[90] While hearing aids can restore hearing perception at least partially, they cannot restore the acuity or fidelity of an intact auditory system.

Public health authorities should not wait for young people to change their PAS listening behaviors. That is unlikely to happen. Meanwhile, the prevalence and severity of NIHL[3,79] and prevalence of tinnitus[91] in PAS users are predicted to increase with lifetime years of personal listening. This is not new information. Berg and Serpanos conducted a cohort study between 2001 and 2008, which identified that PAS users developed significantly increased prevalence of hearing loss and tinnitus.[92] Wasano et al. reported that hearing in Japan at age 40 and younger has become worse in the last 20 years, with PAS use identified as a risk factor.[93] Basner et al. estimated 17%-29% of young PAS users worldwide are at increased risk of NIHL,[3] which is greater than the 5-10% predicted in 2008 by the European Commission's Scientific Committee on Emerging and Newly Identified Health Risks.[75]

A harmonized global manufacturer sound output standard is required to prevent NIHL in PAS users. There are no PAS sound limit standards from any government agency or standard setting organization in the United States or Canada. In 2018, the International Telecommunication Union (ITU) published *Recommendation H.870: Guidelines for safe listening devices/systems*.[65,66] The ITU recommends that PAS device manufacturers include a dosimeter system to track the user's exposure, and provide warnings when their personal listening exceeds a "safe" reference exposure or sound allowance. Dosimeters that measure device sound output may not reliably identify user auditory risk because they do not measure other noise exposures,[61] and PAS sound output can vary widely depending on the device and transducer combination.[69] PAS users can readily learn how to disable safety warnings on the internet. App stores offer volume booster apps, which increase PAS sound intensity, although risk is unknown.

The ITU recommended sound allowances are based on 40-h weekly listening limits, which are inconsistent with the daily 24-h time period used for non-occupational noise exposure limits.[58,59,60] The recommended PAS operational modes of 75 dBA for sensitive users like children and 80 dBA for adults are not protective enough for either population. Therefore, options for volume limiting, parental controls, and "safe" listening information on product packaging and manufacturer's websites could easily give PAS users (or for younger PAS users, their parents) a false perception of hearing health protection.

In occupational health, the excess risk of material hearing impairment is 1% at 80 dBA for the median of the adult worker population.[43] In public health, acceptable risk from any potentially harmful exposure must be close to zero, roughly 1 in 10^4 to 1 in 10^6.[94] As discussed above, the 80 dBA sound allowance places too many PAS users at risk of TTS and NIHL. Humans should not be exposed to noise levels capable of producing TTS.[25,95] For adults, 75 dBA is a compromise between common 70 dBA public and 80 dBA occupational noise limits.[39] Because public health experts consider children are at greater risk from most exposures,[96,97] and because NIHL progression is most rapid in the first 10 to 20 years of noise exposure,[39,47] there should be no compromise on the sound exposure limits for children.

Although NIHL risk in children and teenagers has been estimated to be similar to adults at 70 dBA L_{EQ24h},[59] these estimates and the ITU recommendation do not consider auditory risks beyond NIHL on standard audiometry, noise risk during auditory system development periods, or the greater negative lifetime consequences of early acquired hearing loss in children and teenagers. Safe sound exposures to prevent NIHL in people with pre-existing hearing loss or to prevent tinnitus are unknown, but may be <70 dBA L_{EQ24h}.[39] Additional auditory risks from 70 dBA L_{EQ24h} sound exposure may include auditory neuropathy and HHL.[18] Safe sound exposures to prevent hyperacusis, EHF hearing loss, and SIN hearing loss must be ≤70 dBA, given that HHL precedes NIHL.

The ITU recommendation is unlikely to protect PAS users from auditory damage. ITU places the burden of monitoring personal sound exposure on the PAS user while recommending no specific sound output limits. It is improbable that young people in particular will heed device warnings and safer listening information.[98] Noise education campaigns aimed at convincing PAS users to reduce listening volumes have been largely unsuccessful,[99,100] with NIHL prevalence in PAS users increasing over time despite programs such as Make Listening Safe and Dangerous Decibels. Young people have difficulty understanding future long-term consequences of current behaviors. Listening to loud audio is a common risk taking behavior in teenagers, who rarely respond well to educational efforts.[92]

American automobile manufacturers resisted prioritizing safety in vehicle design until Congress passed the National Traffic and Motor Vehicle Safety Act in 1966, increasing government regulatory oversight over the auto industry.[101] Similarly, progress in preventing hearing loss from PAS and other sound exposures is unlikely without federal legislation regulating PAS and other noise sources. Effective noise control measures to protect PAS user auditory health must include mandatory engineered PAS sound output limits. To prevent NIHL, public health authorities should base PAS global standards on non-occupational daily noise limits. According to the EPA,[58] average noise exposure should never exceed 70 dBA over the 24-hour period, regardless of listening time.[18] To prevent NIHL from recreational sound, Neitzel and Fligor recommended exposure limits of 70 dBA L_{EQ24h} for sensitive populations such as children and 75 dBA L_{EQ24h} for adults.[39] Based on the scientific literature reviewed, we suggest 65 dBA L_{EQ24h} for sensitive PAS users and 70 dBA L_{EQ24h} for adult users. Because of PAS design, delivering high intensity sound directly to the ears, even these sound exposures may not be safe enough to protect auditory health fully from permanent noise damage.

Conclusion

Are current PAS unsafe at any sound like pre-Nader era automobiles were unsafe at any speed? Are there designed-in dangers such that billions of PAS users worldwide are at risk of auditory damage? Unfortunately, the answer is an overwhelming yes. Humans evolved in natural quiet,[23,102] without a high-volume personal soundtrack to our lives. With PAS use, society has the largest unprotected noise-exposed population since before occupational noise exposure standards were introduced in the 1970s. While PAS users might think that they can set PAS listening volumes to avoid auditory injury, high sound output designed into PAS makes personal listening inherently unsafe.

PAS use is a major risk factor for preventable NIHL. Other noise-induced auditory risks in PAS users include tinnitus, hyperacusis, and SIN hearing loss or HHL. Good hearing is important for cognition, communication, socialization, mental health, education, and future employment success. PAS use in children, teenagers, and young adults puts them at high risk of auditory damage and its negative lifelong consequences. As discussed above, early NIHL presages future hearing loss, with progressive deterioration expected from repeated harmful sound exposure. When today's young people reach their mid 40s, many in only 20 years, their hearing may be as bad as their grandparents' hearing is now.

Without engineered PAS sound limits, safer listening approaches include limiting PAS use in childhood, turning intensity limiting, parental controls, or safer listening features to the lowest sound exposure mode, using well fitting transducers with noise-canceling or limiting features, and listening at the lowest comfortable volume setting below 50%. These are unlikely to protect the public because they rely on user motivation instead of noise limits. Reduction of ambient noise levels, e.g. from public transit and road traffic noise, might lessen auditory risk by allowing PAS users to listen at lower, safer sound levels.

PAS can be made safer to use. There is an urgent need for a harmonized global manufacturing standard mandating PAS sound output limits, including devices and transducers, based on non-occupational noise limits. The NIHL risk is well established for >70 dBA L_{EQ24h} daily average noise exposure. It should not be acceptable to leave PAS users of any age vulnerable to auditory damage from dangerously high SPLs. In addition, the PAS manufacturing standard should establish unified volume step output increases, require default start up at lower rather than higher sound exposures, and warn users (or parents) when sound exposure exceeds non-occupational daily limits. Manufacturers could also improve the design of stock or default earbuds to the deeper canal fit or isolator style associated with lower PAS user volume in noisy environments. Warning labels stating, “PAS USE CAUSES HEARING LOSS”, like the warning labels on cigarette packs, may alert users or their parents to the inherent dangers. Safer PAS would better protect public auditory health from noise damage. Without regulated PAS sound limits, preventable NIHL and tinnitus will continue to increase in children, teenagers, and young adults.

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Dr. Fink is board chair of The Quiet Coalition. He serves as an Expert Consultant to the World Health Organization on its Make Listening Safe Program, and as a subject matter expert on noise and the public for the National Center for Environmental Health at the Centers for Disease Control and Prevention. All positions are unpaid and he has no conflicts to disclose. Dr. Fink thanks his noise colleagues David Sykes, Gina Briggs, Jamie Banks, and Jan Mayes, for their help, and his wife, Ruth Cousineau, for her support. His goal is to find a quiet restaurant in which to enjoy the meal and the conversation with her. Dr. Fink also thanks his son Richard for technical support.

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