Noise exposure limit for children in recreational settings: Review of available evidence

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Noise exposure limit for children in recreational settings: Review of available evidence

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It is universally recognized that prolonged exposure to high levels of non-impulsive noise will lead to noise-induced hearing loss. These high levels of noise have traditionally been found in an occupational setting, but exposure to high levels of noise is increasingly common in recreational settings. There is currently no established acceptable risk of hearing loss in children. This review assumed that the most appropriate exposure limit for recreational noise exposure in children would be developed to protect 99% of children from hearing loss exceeding 5 dB at the 4 kHz audiometric test frequency after 18 years of noise exposure. Using the ISO 1999:2013 model for predicting hearing loss, it was estimated that noise exposure equivalent to an 8-h average exposure (L_{EX}) of 82 dBA would result in about 4.2 dB or less of hearing loss in 99% of children after 18 years of exposure. The 8-h L_{EX} was reduced to 80 dB to include a 2 dB margin of safety. This 8-h L_{EX} of 80 dBA is estimated to result in 2.1 dB or less of hearing loss in 99% of children after 18 years of exposure. This is equivalent to 75 dBA as a 24-h equivalent continuous average sound level.
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I. INTRODUCTION

Noise is by far one of the most common environmental exposures and is experienced by almost everyone on a daily basis. Throughout human history, noise has been recognized as a nuisance and, in some cases, an occupational environmental hazard (Berglund *et al.*, 1999). Some of the earliest anecdotal evidence of the effects of hazardous noise exposure were observed in the workplace where it was recognized that coppersmiths suffered from hearing loss (Ramazzini, 1713). As the 20th century progressed, the field of occupational health matured resulting in the promulgation of regulations limiting noise levels in the workplace (Kerr, 2017; Suter, 2003). While occupational noise exposures, at least in industrialized countries, have slightly decreased or at least leveled out, the same cannot be said for non-occupational (noise in the general environment) and recreational noise (i.e., noise sought out for pleasure) (Cheng *et al.*, 2018; Middendorf, 2004; Roberts *et al.*, 2017).

Special consideration must be given to the effects of noise exposure on children as hearing loss can result in lower scholastic achievement, social isolation from their peers, and reduced earning potential that can compound over a child's lifetime (Basner *et al.*, 2014; Evans, 2006; Harrison, 2008; Klatte *et al.*, 2013; Mills, 1975). Children (those under 18 years old) are also more likely than adults to engage in recreational behavior that increases their exposure to high levels of noise such as attending concerts and sports events, or using a personal music player (Jiang *et al.*, 2016; Le Clercq *et al.*, 2016; Rabinowitz, 2010). A study published in 2006 estimated that approximately 16% of young adults (ages 17–25) entering the workforce in the US between 1985 and 2004 had hearing loss greater than 15 dB at the 3, 4, or 6 kHz audiometric test frequencies, but did not find any evidence that the rates of hearing loss were increasing (Rabinowitz *et al.*, 2006). However, the use of personal music players has continued to increase, so it is likely that the percentage of young adults who experience hearing loss from their childhood exposure to hazardous noise levels may increase in the future (WHO, 2017). This presents an issue for the U.S. armed forces as hearing loss was reported to be responsible for 3.4% and 3.5% of disqualifications of first time Army Reserve and National Guard applications, respectively (Walter Reed Army Institute of Research, 2017). Further, hearing loss was reported as being responsible for 10% of existing prior to service (EPTS) discharges (Walter Reed Army Institute of Research, 2017). Even recruits who are admitted with less than disqualifying hearing loss [i.e., <25 dB hearing level (HL) averaged at 0.5, 1.0, and 2.0 kHz, < 35 dB HL at 3.0 kHz, or <45 dB HL at 4.0 kHz] may be expected to have a reduced fitness for duty (Department of Defence, 2018).

While occupational exposure limits for noise have been established, and it is possible to extrapolate these exposure limits from a standard eight hours/day, five days/week work schedule to non-standard work schedules, it is unclear if such adult-based exposure limits would be suitably protective for children who are exposed to recreational noise (Suter, 1988). Additionally, while several exposure limits for environmental noise have been recommended, the limits

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have focused on the general population, and are not specifically intended for children. To specifically protect children from noise-induced hearing loss (NIHL), this report will review the relevant literature and current exposure limits for noise and recommend an exposure limit specifically for recreational noise in children.

A. Overview of the health effects of noise exposure

Noise exposure is most commonly associated with an increased risk of NIHL. However, numerous studies have provided evidence that noise may also be associated with annoyance, sleep disruption, work performance, hypertension, cardiovascular disease (CVD), and learning impairment in children and adults (Basner *et al.*, 2014). While this section provides a brief summary of the health effects of noise exposure, it should not be considered a comprehensive review of the literature on the health effects of noise exposure.

1. Hearing disorders

Noise exposure primarily causes a sensorineural hearing loss which is both preventable and irreversible (Rabinowitz *et al.*, 2006). Early NIHL is generally characterized by a reduced hearing sensitivity at the 3, 4, and 6 kHz audiometric test frequencies with a recovery at lower and higher frequencies (Mirza *et al.*, 2018). Studies of occupational cohorts have found that occupational noise exposure to 80 dBA of steady state (i.e., non-fluctuating) noise will result in minimal (<5 dB) NIHL after 10 years of exposure while occupational exposure to 85 dBA will result in about 10 dB of NIHL after 10 years (Ward *et al.*, 2003). Figure 1 provides an estimate of NIHL at various audiometric frequencies based on different average exposure levels typically encountered in the workplace.

Beyond simply reducing the ability of a person to hear, NIHL has been found to be related to numerous other factors that can increase morbidity and mortality. In an occupational setting, NIHL can make it more difficult for workers to communicate and understand verbal instructions as well as reducing their ability to perceive events (such as alarms or auditory backup signals on heavy machinery) in their environment leading to an increased risk of occupational injury (Cantley *et al.*, 2015; Morata *et al.*, 2005; Picard *et al.*, 2008). In addition, the interference in communication and reduced ability to perceive one's surrounding environment from hearing loss (from either noise or aging) can lead to social isolation and be detrimental to a person's mental health (Stern, 2003). These issues may increase in severity as hearing loss progresses.

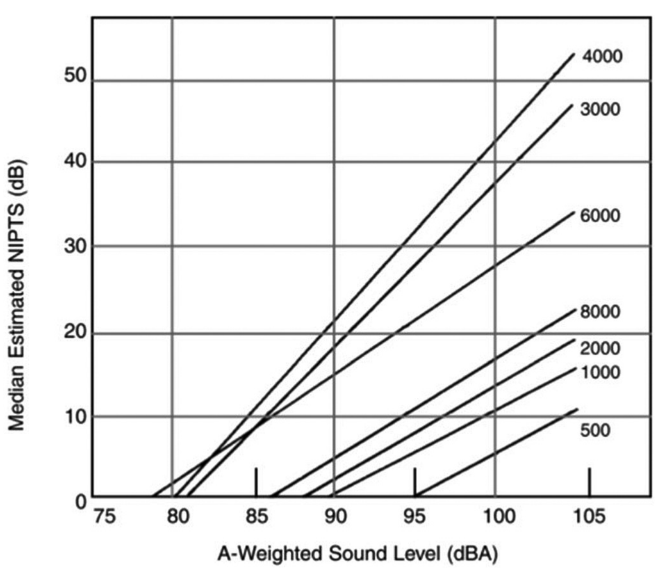

FIG. 1. Estimated hearing loss at different audiometric frequencies from various average levels of occupational exposure to noise (reprinted from the *Noise Manual*, 5th ed.) (Ward *et al.*, 2003).

While not quantifiable like NIHL, tinnitus can range from being a mere annoyance to a debilitating condition. Tinnitus is the perception of a ringing or buzzing in the ears in the absence of any sound in the environment. A cross-sectional study of 3520 individuals between the ages of 12 and 19 estimated a reported that 7.5% of the individuals reported tinnitus lasting more than five minutes over the preceding year, and 4.7% reported suffering from chronic tinnitus (Mahboubi *et al.*, 2013). In a recent systematic review of 25 articles, it is estimated that the prevalence of tinnitus ranges between 6% and 41.9% in the pediatric population (Rosing *et al.*, 2016). Tinnitus can be caused by exposure to impulse noise, such as a gunshot or explosion, but has also been found to be related to chronic noise exposure, NIHL, and aging. A 2017 systematic review and meta-analysis by Lee and Kim (2017) found that hearing loss, being female, and age were risk factors for the development of tinnitus in individuals between the ages of 5 and 20. Tinnitus can be temporary or permanent, and temporary tinnitus can serve as a warning that a person was exposed to hazardous levels of noise (Griest and Bishop, 1998; Mazurek *et al.*, 2010).

The World Health Organization (WHO) estimated that adult onset hearing loss is responsible for 27.4×10^6 disability adjusted life years (DALYs) worldwide in 2008 (WHO, 2008). The economic costs of NIHL are significant, with one study estimating that NIHL costs the US economy between \$58 and \$152 $\times 10^9$ in direct and indirect costs annually (Neitzel *et al.*, 2017).

a. Special considerations for hearing loss in children. As has been noted by numerous organizations and researchers, children are not simply "little adults"; their developing physiology and psychology makes them vulnerable to exposures that that may be less consequential for adults (Mills, 1975). This is particularly true for NIHL in children, as hearing loss can interfere with a child's education by making it difficult to understand information, which can have compounding consequences throughout the child's life (Kattwinkel and Folmer, 2006). A case-control study found that children in the third grade with minimal sensorineural hearing loss (MSHL) (hearing loss from 15 to 40 dB) had significantly lower test scores than their peers without MSHL, although this difference was not seen in the sixth or ninth grade (Bess *et al.*, 1998). Further, the children with MSHL scored worse on a communication, behavioral, energy, stress, social support, and self-esteem tests, and 37% percent of children with MSHL had failed at least one grade

(Bess *et al.*, 1998). In addition, a study of fifth grade students in Malaysia found that poor academic performance was significantly ($p < 0.001$) associated with a mild hearing loss (20–39 dB); however, it was noted that the majority of the students had conductive hearing loss, which is caused by factors other than noise exposure (Khairi Md Daud *et al.*, 2010). While the amount of hearing loss in these studies was relatively mild, it reveals that even a small amount of hearing loss can make it difficult for a listener to accurately perceive speech in an environment that contains competing sources of sound or non-ideal acoustics, such as classrooms or lecture halls (Elliott, 1979; Flexer, 2004; Mills, 1975). In addition, exposure to environmental noise independent of any hearing loss can also lead to worse educational outcomes in children (Belojević *et al.*, 1992; Clark *et al.*, 2006). It is also important to consider that NIHL is irreversible and that the NIHL developed early in life will likely progress as the individual is further exposed to noise, and will follow the child through primary school, university, and in to the workplace and the military, where hazardous levels of noise may also be present. With all these factors in mind, we consider the upper bound hearing loss of 15 dB identified by the review by Tharpe *et al.* (2009) as the cut off for normal hearing in children. However, as Tharpe *et al.* noted, using the term "minimal" to describe the hearing loss suffered by children is misleading because the children with "minimal" hearing loss exhibit more that minimal difficulties.

There is limited evidence that exposure to hazardous noise early in life may lead to hearing loss even after exposure to hazardous noise is ceased. A study of hearing threshold levels (HTLs) in a cohort of 203 men (ages 58–80) enrolled in the Framingham Heart Study found evidence that men who experienced NIHL had an increased level of hearing loss due to age later in life after the exposure to noise ceased (Gates *et al.*, 2000). While this cohort is drastically different than a cohort of children, this research does suggest that noise exposure may still contribute to hearing loss even after the noise has ceased. A more recent study with CBA/CaJ mice found further evidence that noise exposure early in life resulted in greater age related hearing loss, as measured by auditory brainstem response and distortion product otoacoustic emissions compared to mice who were exposed later in life (Kujawa and Liberman, 2006). Currently, there are no longitudinal studies specifically evaluating the effects of noise exposure during childhood and subsequent age-related hearing loss. However, based on what information is currently available in the literature, it appears that noise exposure early in life could have consequences later in life even after exposure has ceased.

2. Non-auditory effects

In addition to NIHL, noise exposure has also been identified as a risk factor for cardiovascular disease (Basner *et al.*, 2014). A study of 1455 blue collar workers found that workers exposed to levels of noise greater than 80 dBA had significantly higher total cholesterol ($p = 0.023$) and triglycerides ($p = 0.001$) than workers exposed to noise below 80 dBA (Melamed *et al.*, 1997). However, there is limited research investigating the relationship between noise exposure and cholesterol and triglyceride levels, and it is possible that other confounding factors could influence this relationship. Noise exposure can also lead to elevated blood pressure levels, even after the exposure to noise has ceased (Chang *et al.*, 2007; Talbott *et al.*, 1999; Zhao *et al.*, 1991). However, it has been noted that the relationship between noise exposure and high blood pressure is likely confounded by other factors in the workplace and that further research is needed to elucidate the relationship between noise and blood pressure (Virkkunen *et al.*, 2005).

Exposure to noise can also lead to annoyance and stress, which can affect the mental wellbeing of workers and the general population. Studies of occupational stress have found that that noise exposure can be a contributor to worker stress and annoyance depending on the type of work being performed (Leather *et al.*, 2003; Melamed *et al.*, 1992). In general, environmental noise is a common complaint as noise levels that are well below levels that can cause hearing loss can still lead to stress, interrupted sleep, and general annoyance (Berglund and Lindvall, 1995; EPA, 1973; Evans, 2006; Evans *et al.*, 2001). However, little research has been conducted to understand the non-auditory effects of noise exposure on children, with the exception of the impact of noise exposure on the academic performance of children in schools.

The results of the RANCH (Road traffic and aircraft noise) study has found that students attending schools around airports had worse reading comprehension and poorer recognition memory after adjusting for social-economic factors (Basner *et al.*, 2017).

The objective of this manuscript was to review the peer reviewed literature and current regulations regarding the effects of recreational noise exposure on children. Specifically, the following research questions were addressed: (1) Are existing exposure limits for occupational noise exposure suitable for determining risk from recreational sound exposure in children; (2) are the recommended exposure limits for recreational noise exposure in adults suitable for determining the risk from recreational sound exposure in children; and (3) what is an appropriate evidenced-based noise exposure limit for children in recreational settings?

II. REVIEW

A. Are existing exposure limits for occupational noise exposure suitable for determination of risk due to recreational sound exposure in children?

1. Occupational noise exposure

Numerous occupational exposure limits for noise have been established by governmental agencies and non-governmental groups (Suter, 2003). Currently the United States Occupational Safety and Health Administration (OSHA) enforces a permissible exposure limit (PEL) of 90 dBA, as an 8-h time weighted average (8-h TWA), with a 5 dB time-intensity exchange rate (ER) (i.e., the L_{AVG}) (OSHA, 2010). Most countries with enforceable occupational exposure limits for noise have chosen to use an exposure limit of 85 dBA with a more protective 3 dB exchange rate (Suter, 2003). This is similar to the recommended

TABLE I. Allowable exposure times for occupational exposure to noise.

Organization		Allowable exposure (dBA) for corresponding time period 16 h	8 h	4 h	2 h	1 h	Peak[a]
EU[b]							
	Lower Exposure Action Value	83	80	83	86	89	135
	Upper Exposure Action Value	88	85	88	91	94	137
	Exposure Limit	90	87	90	93	96	140
NIOSH (US)[c]	Recommended Exposure Limit	88	85	88	91	94	140
OSHA (US)[d]							
	Permissible Exposure Limit	95	90	95	100	105	140
	Action Level	90	85	90	95	100	
Canada (Federal)[e]	Permitted Exposure Level	84	87	90	93	96	
Australia [f]	Permitted Exposure Limit	82	85	88	91	94	140
New Zealand [g]	Permissible Exposure Limit	82	85	88	91	94	140
China [h]	Occupational Exposure Limit	82	85	88	91	94	

[a]Peak noise is measured as unweighted decibels (dB), except for ACGIH, and Australia which uses the C-weighted decibel (dBC).
[b]European Parliament and of the Council (2003).
[c]NIOSH (1998).
[d]Department of Labor (1999).
[e]Government of Canada (2018).
[f]Federal Government of Australia (2015).
[g]Occupational Safety and Health Service (2002).
[h]Ministry of Health and State Administration of Work Safety (2007).

exposure limit put forth by the United States National Institute for Occupational Safety and Health (NIOSH), which is not a legally enforceable limit (NIOSH, 1998). European Union Directive 2003/10/EC (European Parliament and the Council of the European Union, 2003) sets an eight hour time-weighted exposure limit (i.e., the $L_{EX,\ 8h}$) at 87 dBA with a 3 dB ER in addition to specifying lower (80 dBA) and upper (85 dBA) exposure action values (European Parliament and the Council of the European Union, 2003). It is important to consider that these exposure limits are established after accounting for technical, economic, and political feasibility, and often allow for a percentage of the working population to develop NIHL. Table I provides a summary of allowable exposure times according to different governmental agencies and consensus groups.

While the variations between the standards used by OSHA and the rest of the world may seem minor, these differences drastically impact the risk of NIHL in occupational populations (NIOSH, 1998; Suter, 1988, 1992). Figure 2 illustrates the magnitude of the difference in allowable exposure time between the criteria set by OSHA and the criteria set by NIOSH. The curves in Fig. 2 were created using the criteria for the OSHA permissible exposure limit (PEL) (OSHA, 2010), which stipulates an 8-h TWA of 90 dBA with a 5 dB exchange rate, and the NIOSH recommended exposure limit (REL), which recommends a 85 dBA TWA and a 3 dB exchange rate (NIOSH, 1998). These values can be calculated directly using Eq. (1), where T_i is the allowable exposure time for noise exposure L_i, using criterion time T_C (8 h for both OSHA and NIOSH), criterion level L_C (90 dBA for OSHA, 85 dBA for NIOSH), and *ER* is exchange rate (5 dB for OSHA, 3 dB for NIOSH),

$$T_i = \frac{T_C}{2^{(L_i - L_C/ER)}}. \quad (1)$$

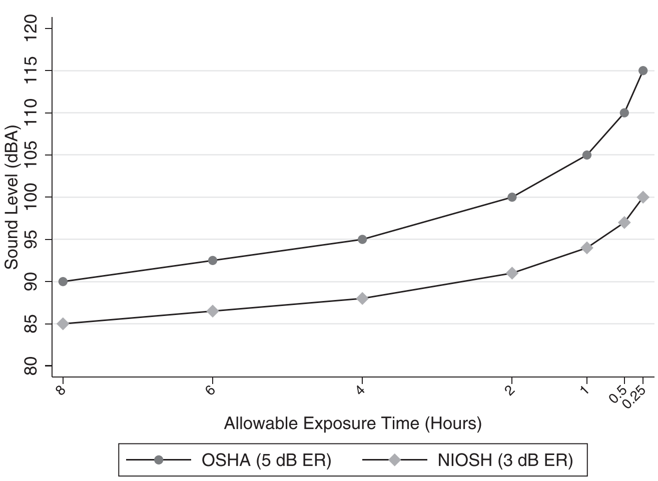

FIG. 2. Allowable exposure time using the OHSA and NIOSH noise criteria.

2. *Applicability of current occupational exposure limits for noise to children recreational noise exposure*

An equivalent continuous average sound level (L_{EQ}) can be calculated over any period of time, typically 8 h for occupational noise exposure (expressed as an L_{EX}, as described above), and 24 h for environmental noise exposure (expressed as an $L_{EQ(24)}$). Equation (1) can be used to calculate the allowable exposure duration from as brief a period as one second to a full 24-h day due to the assumption that equal amounts of sound energy produce equal amounts of hearing damage, regardless of how the energy is distributed in time (Suter, 1992). However, it should be noted that very high levels of noise (e.g., >130–140 dBA) can still lead to

NIHL even when the exposure normalized over a certain time period is below the corresponding exposure limit, due to a different mechanism of damage at very high levels (i.e., mechanical damage vs chronic metabolic damage) (Hamernik *et al.*, 1991).

Despite the fact that occupational exposure limits provide a theoretical and mathematical basis for calculating exposure limits based on any duration of exposure, several shortcomings must be considered when extrapolating from an occupational exposure limit to a non-occupational limit. The first is that occupational exposure limits are a product of political and economic compromises and are not intended to protect all workers from any injury or illness. For example, for exposures at the current OSHA PEL of 90 dBA, approximately 25% of exposed workers are expected to experience an average hearing loss of 25 dB or greater averaged across the 1, 2, 3, and 4 kHz audiometric frequencies after 40 working years of exposure (NIOSH, 1998). Even the more protective occupational exposure limit from NIOSH allows for 8% of the worker population to develop a material hearing loss, an average HTL >25 dBA at the 1, 2, 3, 4 kHz audiometric frequencies, over a 40 year working lifetime (NIOSH, 1998). While the EU does not estimate the percentage of workers who would develop hearing loss with the 87 dBA exposure limit, the model used by NIOSH estimates the risk of material hearing loss to be approximately 13% (NIOSH, 1998). Finally, occupational exposure limits are derived based on the assumption that a worker will be exposed over the course of a normal working lifetime (i.e., about 40 h a week for 40 years), while exposure to recreational noise likely extends over a lifetime and potentially occurs more than 40 h each week (Gopal, 2017; Neitzel and Fligor, 2019; Portnuff *et al.*, 2011).

There are also some practical issues that must be considered when attempting to use occupational exposure limits to develop an exposure limit for children's recreational noise. For example, all regulations regarding occupational noise exposure specify levels at which engineering or administrative noise controls must be implemented (ACGIH, 2017; European Parliament and the Council of the European Union, 2003; OSHA, 2010). In an occupational setting there is, ideally, a health and a safety professional who can use the hierarchy of controls to mitigate the noise hazard by installing engineering controls, limiting a worker's time of exposure, providing appropriate hearing protection, and enrolling a worker in a hearing conservation program (HCP). However, because recreational noise is something that individuals willingly expose themselves to during recreational activities, there are no programmatic approaches or systems in place to mitigate hazardous noise exposure. Children are especially vulnerable because they may not have the knowledge, resources, or desire to take measures to limit their exposure to hazardous levels of noise or even recognize when a noise hazards exists. In addition, occupational exposure limits were developed for adults with fully developed auditory systems; the still-developing systems in children may place them at increased risk of developing auditory dysfunction compared to adults even when exposed to the same levels of noise (Abdala and Keefe, 2012; Kujawa and Liberman, 2006).

While occupational exposure limits provide a theoretical framework from which to begin to estimate risks associated with recreational noise exposure in children, it is not appropriate to simply adopt current occupational exposure limits as recommended exposure limits for children exposed to recreational noise.

B. Are the recommended exposure limits for recreational noise exposure in adults suitable for determination of risk due to recreational sound exposure in children?

1. Current non-occupational exposure limits for noise

Recommended exposure limits for environmental and recreational noise are summarized in Table II. The US Environmental Protection Agency (EPA) and the WHO have both recommended exposure limits for environmental noise. The EPA sets a 24-h ($L_{EQ(24)}$) of 70 dBA using the 3 dB ER in order to prevent NIHL (Berglund *et al.*, 1999; EPA, 1974). This is equivalent to an 8-h L_{EX} of 75 dBA assuming that any noise exposure outside of that 8-h is below 60 dBA. This limit was designed to protect 96% of the general

TABLE II. Environmental and recreational noise exposure limits.

Organization		L_{AEQ} (dBA)	Exposure Time (Hours)	L_{MAX}	Notes
WHO					
1999[a]	Entertainment events	100	4	110	< 5 occurrences per year
1999[a]	Entertainment events	97	8	110	< 5 occurrences per year
1999[a]	Sound through headphones	85	1	110	
1999[a]	Sound through headphones	76	8	110	
1999[a]	Sound through headphones	70	24		
2017[b]	Recreational noise (no risk of NIHL)	75	8		
2017[b]	Recreational noise (minimal risk of NIHL)	83	8		
EPA					
1974[c]	Recommended exposure limit	75	8		
1974[c]	Recommended exposure limit	70	24		

[a]Berglund *et al.* (1999).
[b]Neitzel and Fligor (2019).
[c]EPA (1974).

population from hearing loss greater than 5 dB at the 4 kHz audiometric frequency. The EPA has estimated that that after 10 years of exposure the average hearing loss at the 4 kHz audiometric frequency would be 4, 9, and 15 dB HL at exposures of 80, 85, and 90 dBA L_{EX}, respectively. The WHO also recognized that hearing impairment was unlikely for L_{EX} exposures below 75 dBA or $L_{EQ(24)}$ below 70 dBA, and so established a recommended limit of 70 dBA $L_{EQ(24)}$, consistent with the EPA recommendation (Berglund *et a*l., 1999; EPA, 1974).

Unlike the EPA in its guidelines for community noise, the WHO addressed noise exposure in specific environments, and suggested that patrons of entertainment venues should not be exposed to sounds levels greater than 100 dBA during a four-hour period (97 dBA L_{EX}) more than four times per year. The WHO also recommended that the L_{MAX} should always be kept below 100 dBA (Berglund *et al.*, 1999). The WHO advised that the $L_{EQ(24)}$ should be kept below 70 dBA for music played through headphones, or limited to one hour at 85 dBA, and that music exposure should never exceed 110 dBA (Berglund *et al.*, 1999).

In 2017, the WHO published a review of the risk of NIHL due to recreational noise. In this report, a limit of 75 dBA as an 8-h L_{EX} was recommended to completely eliminate the risk of hearing loss, while a L_{EX} of 83 dBA was recommended to minimize, but not eliminate, the risk of hearing loss (Neitzel and Fligor, 2019). This report recommended that young children who are not expected to have the autonomy to make health decisions would be best protected by adopting the 75 dBA limit, but no further recommendations for recreational noise exposure in children were considered.

2. Applicability of existing non-occupational exposure limits for noise to children

Unlike occupational noise regulations, environmental noise exposure limits seek to protect almost all individuals from hearing damage. The WHO has specifically suggested limits for recreational noise exposure based on the risk of hearing loss. However, in its 1999 guidelines for community noise, the WHO does not provide a quantitative risk assessment of hearing loss at its suggested levels of recreational noise exposure, which makes it unclear if these standards are applicable to children (Berglund *et al.*, 1999). The 2017 WHO report provided a recommended exposure limit for recreational noise in the general population but did not recommended an exposure limit specifically for children (Neitzel and Fligor, 2019). Instead, this report simply recommended that childhood exposures to noise be kept to as low as possible without considering the excess risk of NIHL in children from various levels of exposure.

In addition, special consideration must be made for the use of personal listening devices (PLDs) by children. A recent review by Jiang *et al.* (2016) noted that the average 8-h L_{EX} for noise exposure from devices PLDs ranged between 61.6 and 87.2 dBA, with the average sound level of the PLDs being correlated with the background noise levels present in the listener's environment. However, it is important to consider that reported listening times can significantly vary; for example, one study found that the median listening time of PLDs was 2 h per day, with a range of 0.5 to 5.75 h per day (Portnuff *et al.*, 2011). In addition to PLDs, other sources of recreational noise exposure, including attending sporting events, concerts, and other noisy activities, can expose an individual to an L_{EX} ranging from 79 to 130 dBA (Gopal, 2017). While these studies looked at some of the most common sources of recreational noise, there are numerous other recreational activities where noise levels and exposure duration and frequency have not been not well characterized. Some of the recreational noise levels reported in the literature would be expected to produce hearing loss at the 4 kHz frequency that would exceed 5 dB after 18 years of exposure, which likely partially explains hearing loss observed in young adults entering the workforce (Rabinowitz *et al.*, 2006; Seixas *et al.*, 2012). Interestingly, two recent analyses of the National Health Examination Survey (NHES) and the National Health and Nutrition Examination Survey (NHANES) have found that overall hearing impairment in young people has decreased (Hoffman *et al.*, 2018; Su and Chan, 2017). Hoffman *et al.* speculated that this improvement in hearing may be partially attributable to broader public health measure such as improved immunization rates for diseases such as measles, mumps and rubella, decreased youth smoking rates, and economic factors that have reduced the number of manufacturing and farming jobs that are available to young people (Hoffman *et al.*, 2018).

III. WHAT ARE THE APPROPRIATE EVIDENCE-BASED EXPOSURE LIMITS FOR CHILDREN (IN RECREATIONAL SETTINGS)?

A. Recommended exposure limit for children exposure to recreational noise

1. Continuous noise

While complete elimination of any NIHL should be the ultimate goal of a recommended exposure limit, it is worthwhile to consider the level of exposure below which the vast majority (99%) of the population will be protected from NIHL that results in functional impairment. For the purposes of this document, the recommended exposure limit for recreational noise exposure in children should prevent hearing threshold shifts of more than 5 dB at the 4 kHz frequency after 18 years of exposure. The 5 dB fence was chosen because changes in hearing level less than 5 dB are not noticeable or measurable using conventional audiometry, and the 4 kHz audiometric frequency was chosen because it is the most susceptible to NIHL. Thus, by limiting hearing loss in the 4 kHz frequency, the recommended limit will also protect hearing in the other audiometric frequencies (EPA, 1974).

ISO model 1999:2013 (ISO, 2013) allows for the estimation of hearing threshold levels when accounting for aging and noise exposure in a highly screened, otologically normal adult population. Because the ISO model uses a baseline age of 18 for its calculation of hearing loss, the model cannot be used to predict hearing loss due to aging in children. However, it can be used to predict NIHL. The ISO

1999 model assumes that the statistical distribution of NIHL follows the Gaussian (normal) distribution, thus it is possible to select a Z-score that allows the calculation of the 99th percentile of NIHL on the distribution using a standard Z-table. The median (50th percentile) NIHL can be calculated for the 4 kHz audiometric frequency using Eq. (2), where N_{50} is the predicted median NIPTS, μ and v represent frequency dependent correction factors, t represents the length of exposure, t_0 represents 1 year, L_{EX} represents the continuous noise exposure for an 8-h working day, and L_0 represents the frequency dependent sound level at which effect on hearing is negligible,

$$N_{50} = \left[\mu + v \times log\left(\frac{t}{t_0}\right)\right] \times (L_{EX,8h} - L_0)^2. \quad (2)$$

The 99th percentile can then be calculated using Eq. (3), where N_{99} is the predicted 99th percentile of NIPTS, k is the Z-score corresponding to the 99th percentile (2.576) and d_u is the correction factor used to characterize the upper part of the statistical distribution for NIPTS as specified by the ISO 1999:2013 method (ISO, 2013)

$$N_{99} = N_{50} + k \times d_u. \quad (3)$$

A curve of the estimated NIPTS at the 99th percentile after 18 years of exposure for sound levels between 75 and 100 dBA is presented in Fig. 3. Based on the results of the model, 99% of children exposed to recreational noise equivalent to an L_{EX} of 82 dBA would be expected to have NIHL of 4.2 dB or less at the 4 kHz audiometric frequency after 18 years of exposure. This is slightly below the 5 dB fence that the EPA considers significant (EPA, 1974).

If recreational noise exposure only lasted during childhood and subsequent exposure from the workplace and general environment was insignificant, then it would be reasonable to adopt a recommended exposure limit of 82 dBA. However, as the average life expectancy in industrialized countries increases, it is quite likely that the cumulative duration of recreational noise exposure will continue to increase, leading to NIHL in excess of the predictions from the ISO model. In addition, the estimates produced by the ISO model are based on studies of adult populations in industrialized nations and may not be generalizable to children who do not have a fully mature auditory system. Any NIHL due to recreational noise during childhood would be in addition to hearing loss suffered from occupational exposures, which are significant for many workers and members of the military (Masterson *et al.*, 2016; Yong and Wang, 2015). Because of these factors, it is prudent to adopt a margin of safety for the recommended exposure limit. A margin of safety of 3 dB (bringing the exposure limit to 79 dBA) would result in a halving of the sound power. However, because the 82 dBA exposure limit was already derived using conservative assumptions, and because the difference in estimated hearing loss between 79 and 80 dBA is miniscule (approximately 0.75 dB HL) at 4 kHz the recommended exposure limit for recreational noise for children should be 80 dBA as an 8-h L_{EX}. Adherence to an exposure limit of 80 dBA will protect 99% of children from more than 2.1 dB of hearing loss from recreational noise throughout their childhood. This exposure limit is equivalent to a $L_{EQ(24)}$ of 75 dBA. In addition to the aforementioned reasons for applying a margin of safety to help account for uncertainties in the estimate, we also believe that from a public health promotion standpoint it is advantageous to use an 80 dBA limit because it is a round number and easier to remember.

This exposure limit is more protective than the current occupational exposure limit of 87 dBA in the EU (European Parliament and the Council of the European Union, 2003), the current recommended exposure limit of 85 dBA from (NIOSH, 1998), and the 83 dBA exposure limit recommended by Neitzel and Fligor (2019) for exposure to recreational noise in the general population among individuals willing to tolerate a small risk of NIHL (Fig. 4). The allowable exposure duration at various levels of noise can be determined by using Fig. 5, which was calculated using Eq. (1).

2. Impulse noise

Impulse noise occurs over a very short duration and can have much higher sound pressure levels than continuous

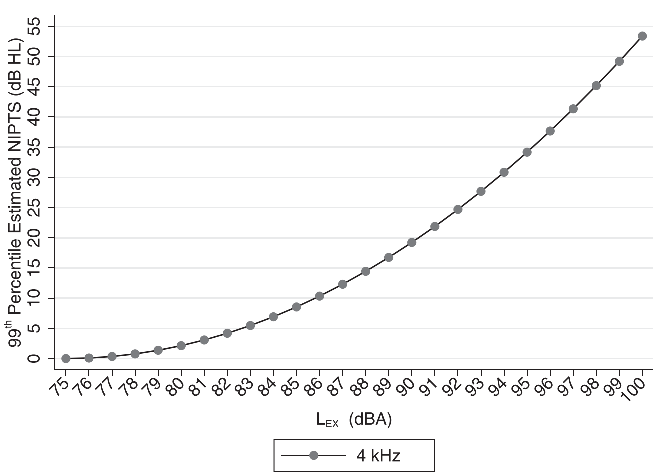

FIG. 3. Estimated levels of hearing loss for the 99th percentile of the population at the 4 kHz frequency after 18 years of exposure.

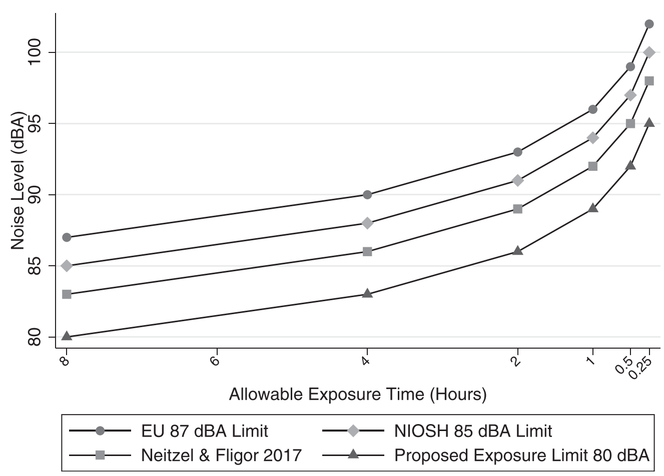

FIG. 4. Allowable exposure time using the EU, NIOSH, Neitzel and Fligor (2019), and the current recommended exposure limit.

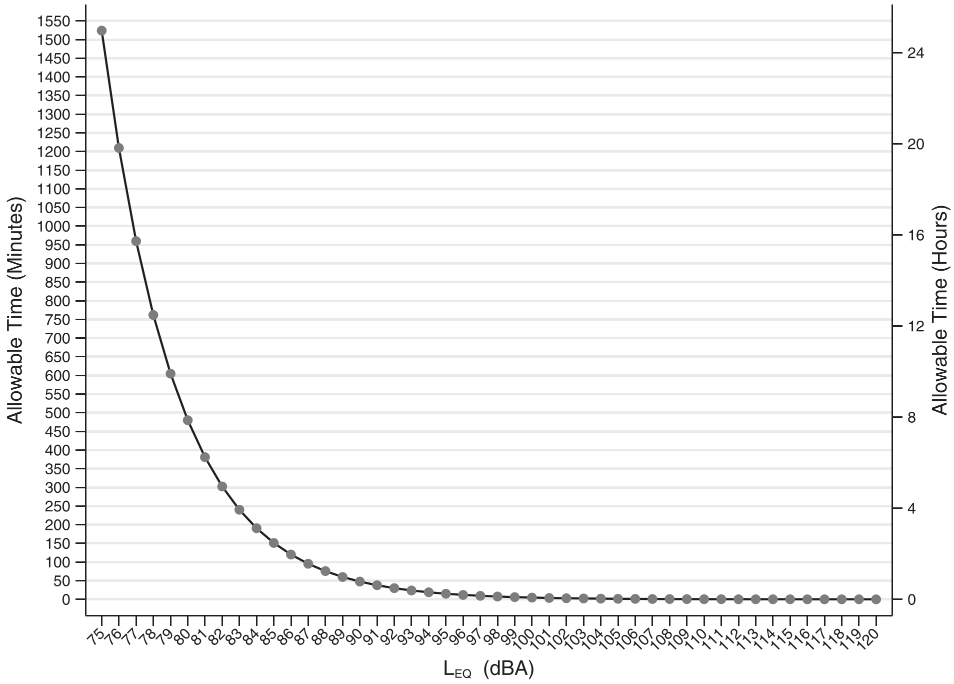

FIG. 5. Allowable exposure time (minutes) at various levels of noise exposure based on the recommended exposure limit.

noise. At high enough levels, impulse noise can cause immediate, irreversible acoustical trauma. A limit for impulse noise cannot be directly derived using the ISO 1999 standard. Several organizations have set a limit of 140 dB for impulse noise in occupational settings (OSHA, 2010), and the military (U.S. Department of Defense, 2015). Price (1981) summarized the evidence from temporary threshold shift, electrophysiological, and histological studies to estimate a critical level (CL) for impulse noise. It was found that there was a mean CL of 145 dB with an 8 dB standard deviation. Based on this data, it was estimated that a CL of 132 dB would protect the hearing of the fifth percentile of the most vulnerable individuals (Price, 1981). The WHO suggested a limit to impulse noise of 120 dB for children but did not provide a rationale for why this level was chosen (Berglund *et al.*, 1999). In its criteria document, NIOSH did not set a specific limit for impulse noise, but rather elected to assume that the L_{EQ}, based on the equal energy hypothesis, was sufficiently protective regardless of whether the effects of impulse noise were additive or synergistic with continuous noise (NIOSH, 1998). A more recent analysis conducted by NIOSH compared the MIL-STD 1474D, the 8-h L_{EQ}, and the Auditory Hazard Assessment Algorithm for Human (AHAAH) using the Albuquerque Blast Overpressure exposures. This analysis found that the L_{EQ} provided the best sensitivity and specificity for discrimination of potential hazards (Murphy and Kardous, 2012).

The issue of impulse noise is further complicated by the fact that accurate measurement of impulse noise is technically challenging. However, the rapid rise and fall in sound pressure level makes it easy for individual to detect when they are in the presence of impulse noise. In lieu of providing a formal exposure limit, we recommend that children are exposed to impulse noise as little as possible. In the event impulse noise is expected (e.g., firearms, explosives, etc.), double hearing protection (i.e., ear plugs and earmuffs) should be utilized to reduce the risk of incurring hearing loss. If policy-makers wish to adopt a formal standard for impulse noise, it would be best to adopt the WHO standard for impulse noise of 120 dBA.

B. Uncertainties and limitations in the recommended exposure limit

The recommended exposure limit of 80 dBA L_{EX} was established based on the assumption that less than 1% of exposed children experiencing hearing loss greater than 5 dB at the 4 kHz audiometric frequency would be considered "acceptable." Acceptable risk is established after considering economic, social, and technical factors that cannot be comprehensively considered in this analysis. Thus, the criteria used here were chosen based on the assumption that it is in a society's best interest to protect nearly all children from any measurable harm. Should the risk of less than 1% of children experiencing more than 5 dB HL of hearing loss be found unacceptably high, an exposure limit of 75 dBA L_{EX} would protect virtually all children from hearing any loss (see Fig. 3).

Several uncertainties were considered in deriving the recommended exposure limit of 80 dBA and, where possible, the most conservative (i.e., protective) assumptions were made in order to maximize the protection provided by this exposure limit. For example, the recommended limit assumes that a child will be exposed to recreational noise consistently from birth until age 18. While the literature suggests that the duration of recreational noise exposure can vary substantially, it is unlikely that a child be exposed to substantial recreational noise immediately following birth, though it is certainly possible that once a child begins to engage in recreational noise that they will do so at high levels and for extended durations (Gopal, 2017). In addition, the decision to use the 4 kHz audiometric frequency in the risk assessment likely yielded an overly conservative exposure limit, as the 4 kHz audiometric frequency is recognized as being the most vulnerable to hearing loss in adults. The decision to develop an exposure based on preventing more than 5 dB of hearing loss at this frequency is also conservative when compared to the lower bound of MIHL (15 dB) identified by (Tharpe *et al.*, 2009) and contemporary occupational exposure limits, which are based on more substantial losses of 25 dB HL or greater.

Uncertainty also arises because the ISO 1999 model is intended for an otologically normal adult (>18 years) population (ISO, 2013; Williams *et al.*, 2015). However, extrapolation of the model is necessary because there is not currently a hearing loss model specific to children. There is some evidence that children are more vulnerable to hearing loss at the 6 kHz audiometric frequency (Niskar *et al.*, 2001), but the data (from adults) that underlie the ISO model predict that the greatest hearing loss from noise will occur at 4 kHz. Nevertheless, it is expected that the immediate damage to hearing threshold levels from hazardous noise exposure would affect children in a similar manner as adults. Additionally, the recommended exposure limit was chosen to limit NIHL to below 5 dB in the 99th percentile of the population, which is in the extreme right tail of the normal distribution, and as a result the model relies on less experimental data (ISO, 2013). However, the results of a sensitivity analysis using the ISO1999 model found that the difference in estimated NIHL between the 95th and 99th percentile was <0.3 dB, suggesting that using the 99th as opposed to the 95th percentile would not change the conclusions of this report.

Another limitation of this recommended exposure limit is that it was developed to protect only the auditory system in children. There is evidence to suggest that the non-auditory effects of noise exposure occur at lower levels than those associated with NIHL (Basner *et al.*, 2014). While there is evidence of non-auditory effects resulting from noise exposure in adults, very little research has been conducted in specifically in children with the exception of cognitive impacts, which are well beyond the scope of this report. Thus, it was not appropriate to assess the risk of non-auditory effects of noise exposure in children when developing this recommended exposure limit. However, it is worth noting that there is some evidence that desired noise (e.g., music, white noise, etc.) may have a positive non-auditory effects as opposed to negative non-auditory effects generally associated with environmental noise (Ando, 2001; Harrison and Kelly, 1989).

There has been an increased interest in measuring noise-induced changes in the auditory system other than loss of audiometric hearing sensitivity. This is often referred to as "hidden hearing loss." Research on hidden hearing loss is ongoing, and it is possible that even if this limit is adhered to, profound and permanent loss of cochlear-nerve synapses may occur (Kujawa and Liberman, 2015). Most of the relevant research has measured cochlear synaptopathy (dysfunction of the synapses in the ear) in animal models after two hours of exposure to between 100 and 108 dB of sound (Kujawa and Liberman, 2009). However, a threshold for such damage has not been identified in humans (Guest *et al.*, 2017). There is speculation that this type of cochlear synaptopathy can lead to difficulty interpreting speech in noisy environments, which is of particular concern for children who spend a significant amount of time receiving instruction in classrooms (Grinn *et al.*, 2017). However, Grinn *et al.* noted that the small temporary threshold shift (TTS) in a study of 26 participants after exposure to recreational noise indicated that there was little risk of synaptopathy and did not indicate that recreational noise exposure was likely to result in hidden hearing loss (Grinn *et al.*, 2017). Further, a study conducted by Le Prell *et al.* (2018) failed to find a relationship between recreational noise exposure and speech-in-noise deficits, which was being used as a function indicator of hidden hearing loss in a small cohort of college students (Le Prell *et al.*, 2018). The recommended exposure limit was established to limit NIHL based on the audiogram, but if adhered to this limit may also help limit damage to cochlear synapses. Until a relationship between noise exposure and cochlear synaptopathy can be established, increased incidence of tinnitus, high frequency audiometry, and otoacoustic emissions, may serve as more sensitive warnings of early noise-induced damage (Avan *et al.*, 2013; Griest and Bishop, 1998; Guest *et al.*, 2017; Mehrparvar *et al.*, 2011).

Another limitation is that this recommended exposure limit assumes that the only significant source of noise exposure comes from recreational exposure. However, if a child is employed in a noisy profession or is exposed to significant environmental noise, then this recommended exposure limit may not be sufficiently protective.

C. Recommendations for reducing noise exposure

Recreational noise is more difficult to control than occupational noise, since the exposure is something that is desired and actively sought out and the duration, frequency, and intensity of exposure can vary substantially from person to person. Controlling this exposure is even more challenging because young children often do not have the autonomy to reduce their exposure to noise and older children may, due to lack of knowledge or social pressure, actively seek out recreational environments or activities that have hazardous levels of noise. There are several practical guidelines that can be implemented by both a child or their parent that can be used to reduce a child's exposure to recreational noise. The feasibility of these recommendations will vary based on the age of the child, but in many instances the best approach may be for parents to attend noisy events without their children, or to seek out quieter, "child-friendly" events.

We recommend four different exposure reduction strategies for children:

(1) Use noise-reducing or noise-canceling headphones or earbuds when using PLDs. Jiang *et al.* (2016) noted in their review of noise exposure from PLDs that background noise levels were correlated ($r = 0.70$; $p < 0.05$) with higher listening levels on PLDs (Jiang *et al.*, 2016). Noise canceling headphones help block noise from the general environment and have been found to reduce listening levels by 4 dBA (Liang *et al.*, 2012).
(2) Educational interventions should be provided to each child to encourage the child to adopt safe listening habits; to identify environments where hazardous levels

of noise may exist so they can be avoided; and to utilize hearing protection as necessary in environments with high levels of noise. Several organizations, such as Dangerous Decibels have already developed effective public health intervention programs. However, it has been demonstrated that the effect of these interventions are transient and children must be continuously engaged in these programs (Griest *et al.*, 2007; Martin *et al.*, 2013). Further educational are available from the WHO, and the U.S. National Institutes of Health (National Institutes of Health, 2019; WHO, 2017)

   (a) In addition to utilizing educational campaigns, it is also useful to institute a rule of thumb to help guide children and their parents in safe listening habits. The WHO has suggested that PLD volume be set no higher than 60% of the maximum volume (WHO, 2017). Alternatively, Portnuff (2016) noted that the recommendation suggested by the WHO may be too restrictive for adolescents and suggested that a more realistic guideline would be to suggest that PLD users limit their exposure to 80% of the maximum volume for 90 min per day (Portnuff, 2016). Regardless of the specific level specified, the concept that listening at the maximum volume is undesirable and likely to result in excessive exposure is a key message that needs to be communicated to users.

(3) Limit participation in sporting events, concerts, and other activities where noise levels are likely to be excessively high. While the duration of exposure from these locations are generally lower than that of PLDs, the levels of noise can be much higher, ranging from 79 to 130 dBA (Gopal, 2017).

   (a) When these types of events are attended, hearing protection should be worn regardless of the duration of exposure. It has been well documented that children imitate their parents; therefore, it is recommended that parents and other adults also utilize hearing protection in order to model proper behavior for the child (Hoehl *et al.*, 2019). There are specialized hearing protection devices available to protect the user from noise while not hampering the quality of the sound in these environments.

(4) Utilize smart devices to measure noise exposure of venues and activities to determine if noise exceeds 80 dBA and adjust behaviors and exposure as necessary. Numerous applications are available, but the sound level meter application released by NIOSH is recommended for iOS devices, while the SoundMeter application is recommended for Android devices based on previous assessment of the applications' accuracy (Kardous and Shaw, 2016; Roberts *et al.*, 2016).There is evidence to suggest that an uncalibrated smartphone can provide reasonably accurate measurement of noise levels across a limited range of sound pressure levels (Murphy and King, 2016). However, it should be noted that these devices cannot be used to measure impulse noise and are not as accurate as traditional dosimeters. Therefore, these should only be used for general guidance and educational purposes

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Abdala, C., and Keefe, D. H. (**2012**). "Morphological and functional ear development," in *Human Auditory Development*, edited by L. Werner, A. Popper, and R. Fay (Springer-Verlag, New York), pp. 19–59.

ACGIH (**2017**). *2017 TLVs and BEIs* (ACGIH, Cincinnati, OH).

Ando, Y. (**2001**). "Differential effects of noise and music signals on the behavior of children," J. Sound Vib. **241**, 129–140.

Avan, P., Büki, B., and Petit, C. (**2013**). "Auditory distortions: Origins and functions," Physiol. Rev. **93**, 1563–1619.

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., and Stansfeld, S. (**2014**). "Auditory and non-auditory effects of noise on health," Lancet **383**, 1325–1332.

Basner, M., Clark, C., Hansell, A., Hileman, J. I., Janssen, S., Shepherd, K., and Sparrow, V. (**2017**). "Aviation noise impacts: State of the science," Noise Heal. **87**, 41–50.

Belojević, G., Öhrström, E., and Rylander, R. (**1992**). "Effects of noise on mental performance with regard to subjective noise sensitivity," Int. Arch. Occup. Environ. Health **64**, 293–301.

Berglund, B., and Lindvall, T. (**1995**). *Community Noise* (World Health Organiza, Stockholm, Sweden), available at http://www.nonoise.org/library/whonoise/whonoise.htm#4 (Last viewed January 15, 2018).

Berglund, B., Lindvall, T., and Schwela, D. (**1999**). "Guidelines for community noise," https://apps.who.int/iris/bitstream/handle/10665/66217/a68672.pdf?sequence=1&isAllowed=y (Last viewed January 15, 2018).

Bess, F., Dodd-Murphy, J., and Parker, R. (**1998**). "Children with minimal sensorineural hearing loss- prevalence, educational performance, and functional status," Ear Hear. **19**, 339–354.

Cantley, L. F., Galusha, D., Cullen, M. R., Dixon-Ernst, C., Rabinowitz, P. M., and Neitzel, R. L. (**2015**). "Association between ambient noise exposure, hearing acuity, and risk of acute occupational injury," Scand. J. Work. Environ. Health **41**, 75–83.

Chang, T.-Y., Su, T.-C., Lin, S.-Y., Jain, R.-M., and Chan, C.-C. (**2007**). "Effects of occupational noise exposure on 24-hour ambulatory vascular properties in male workers," Environ. Health Perspect. **115**, 1660–1664.

Cheng, W., Roberts, B., Mukherjee, B., and Neitzel, R. L. (**2018**). "Meta-analysis of job exposure matrix data from multiple sources," J. Expo. Sci. Environ. Epidemiol. **28**, 259–274.

Clark, C., Martin, R., Van Kempen, E., Alfred, T., Head, J., Davies, H. W., Haines, M. M., Lopez Barrio, I., Matheson, M., and Stansfeld, S. A. (**2006**). "Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension: The RANCH project," Am. J. Epidemiol. **163**, 27–37.

Department of Defence (**2018**). *Medical Standards for Appointment, Enlistment, or Induction Into the Military Services* (DOD, Washington, DC).

Department of Labor (**1999**). *Health Standards for Occupational Noise Exposure; Final Rule* (U.S. Congress, Washington, DC).

Elliott, L. L. (**1979**). "Performance of children aged 9 to 17 years on a test of speech intelligibility in noise using sentence material with controlled word predictability," J. Acoust. Soc. Am. **66**, 651–653.

EPA (**1973**). *Public Health and Welfare Criteria for Noise* (EPA, Washington, DC).

EPA (**1974**). *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare With an Adequate Margin of Safety* (EPA, Washington, DC).

European Parliament and the Council of the European Union (**2003**). *Minimum Health and Safety Requirements Reagarding the Exposure of Workers to the Risks Arising from Physical Agents (Noise)*, Directive 2003/10/EC (European Parliament and the Council of the European Union, Strasbourg, France).

Evans, G. W. (**2006**). "Child development and the physical environment," Ann. Rev. Psychol. **57**, 423–451.

Evans, G. W., Lercher, P., Meis, M., Ising, H., and Kofler, W. W. (**2001**). "Community noise exposure and stress in children," J. Acoust. Soc. Am. **109**, 1023–1027.

Federal Government of Australia (**2015**). *Work Health and Safety (Managing Noise and Preventing Hearing Loss at Work)* (Federal Government of Australia, Canberra, Australia).

Flexer, C. (**2004**). "The impact of classroom acoustics: Listening, learning, and literacy," Semin. Hear. **25**, 131–140.

Gates, G. A., Schmid, P., Kujawa, S. G., Nam, B. H., and D'Agostino, R. (**2000**). "Longitudinal threshold changes in older men with audiometric notches," Hear. Res. **141**, 220–228.

Gopal, K. (**2017**). *Current Practices in the Assessment of Recreational Noise-induced Hearing Loss: A Review* (World Health Organization, Geneva, Switzerland).

Government of Canada (**2018**). *Canada Occupational Health and Safety Regulations* (Government of Canada, Quebec, Canada).

Griest, S. E., and Bishop, P. (**1998**). "Tinnitus as an early indicator of permanent hearing loss: A 15 year longitudinal study of noise exposed workers," AAOHN J. **46**, 325–329.

Griest, S. E., Folmer, R. L., and Martin, W. H. (**2007**). "Effectiveness of 'dangerous decibels,' a school-based hearing loss prevention program," Am. J. Audiol. **16**, 165–182.

Grinn, S. K., Wiseman, K. B., Baker, J. A., and Le Prell, C. G. (**2017**). "Hidden hearing loss? No effect of common recreational noise exposure on cochlear nerve response amplitude in humans," Front. Neurosci. **11**, 465.

Guest, H., Munro, K. J., Prendergast, G., Howe, S., and Plack, C. J. (**2017**). "Tinnitus with a normal audiogram: Relation to noise exposure but no evidence for cochlear synaptopathy," Hear Res. **344**, 265–274.

Hamernik, R. P., Ahroon, W. A., and Hsueh, K. D. (**1991**). "The energy spectrum of an impulse: Its relation to hearing loss," J. Acoust. Soc. Am. **90**, 197–204.

Harrison, R. (**2008**). "Noise-induced hearing loss in children: A 'less than silent' environmental range," Paediatr. Child Heal. **13**, 377–382.

Harrison, D. W., and Kelly, P. L. (**1989**). "Age differences in cardiovascular and cognitive performance under noise conditions," Percept. Mot. Skills **69**, 547–554.

Hoehl, S., Keupp, S., Schleihauf, H., Mcguigan, N., Buttelmann, D., and Whiten, A. (**2019**). " 'Over-imitation': A review and appraisal of a decade of research," Dev. Rev. **51**, 90–108.

Hoffman, H. J., Dobie, R. A., Losonczy, K. G., Themann, C. L., and Flamme, G. A. (**2018**). "Kids nowadays hear better than we did: Declining prevalence of hearing loss in US youth, 1966–2010," Laryngoscope **129**, 1922–1939.

ISO (**2013**). ISO 1999:2013, *Acoustics—Estimation of Noise-Induced Hearing Loss* (ISO, Geneva, Switzerland).

Jiang, W., Zhao, F., Guderley, N., and Manchaiah, V. (**2016**). "Daily music exposure dose and hearing problems using personal listening devices in adolescents and young adults: A systematic review," Int. J. Audiol. **55**, 197–205.

Kardous, C., and Shaw, P. (**2016**). "Evaluation of smartphone sound measurement applications (apps) using external microphones—A follow-up study," J. Acoust. Soc. Am. **140**, EL327–EL333.

Kattwinkel, J., and Folmer, R. L. (**2006**). "Noise-induced hearing loss in young people," Pediatrics **117**, 248–249.

Kerr, M. J. (**2017**). "Historical review of efforts to reduce noise-induced hearing loss in the United States," Am. J. Ind. Med. **60**, 569–577.

Khairi Md Daud, M., Noor, R. M., Rahman, N. A., Sidek, D. S., and Mohamad, A. (**2010**). "The effect of mild hearing loss on academic performance in primary school children," Int. J. Pediatr. Otorhinolaryngol. **74**, 67–70.

Klatte, M., Bergström, K., and Lachmann, T. (**2013**). "Does noise affect learning? A short review on noise effects on cognitive performance in children," Front. Psychol. **4**, 1–6.

Kujawa, S. G., and Liberman, M. C. (**2006**). "Acceleration of age-related hearing loss by early noise exposure: Evidence of a misspent youth," J. Neurosci. **26**, 2115–2123.

Kujawa, S. G., and Liberman, M. C. (**2009**). "Adding insult to injury: Cochlear nerve degeneration after 'temporary' noise-induced hearing loss," J. Neurosci. **29**, 14077–14085.

Kujawa, S. G., and Liberman, M. C. (**2015**). "Synaptopathy in the noise-exposed and aging cochlea: Primary neural degeneration in acquired sensorineural hearing loss," Hear. Res. **330**, 191–199.

Leather, P., Beale, D., and Sullivan, L. (**2003**). "Noise, psychosocial stress and their interaction in the workplace," J. Environ. Psychol. **23**, 213–222.

le Clercq, C. M. P., van Ingen, G., Ruytjens, L., and van der Schroeff, M. P. (**2016**). "Music-induced hearing loss in children, adolescents, and young adults," Otol. Neurotol. **37**, 1208–1216.

Lee, D. Y., and Kim, Y. H. (**2017**). "Risk factors of pediatric tinnitus: Systematic review and meta-analysis," Laryngoscope **128**, 1462–1468.

Le Prell, C. G., Siburt, H. W., Lobarinas, E., Griffiths, S. K., and Spankovich, C. (**2018**). "No reliable association between recreational noise exposure and threshold sensitivity, distortion product otoacoustic emission amplitude, or word-in-noise performance in a college student population," Ear Hear. **39**, 1057–1074.

Liang, M., Zhao, F., French, D., and Zheng, Y. (**2012**). "Characteristics of noise-canceling headphones to reduce the hearing hazard for MP3 users," J. Acoust. Soc. Am. **131**, 4526–4534.

Mahboubi, H., Oliaei, S., Kiumehr, S., Dwabe, S., and Djalilian, H. R. (**2013**). "The prevalence and characteristics of tinnitus in the youth population of the United States," Laryngoscope **123**, 2001–2008.

Martin, W. H., Griest, S. E., Sobel, J. L., and Howarth, L. C. (**2013**). "Randomized trial of four noise-induced hearing loss and tinnitus prevention interventions for children," Int. J. Audiol. **52**, S41.

Masterson, E. A., Bushnell, T., Themann, C., and Morata, T. C. (**2016**). "Hearing impairment among noise-exposed workers—United States, 2003–2012," Morb. Mortal. Wkly. Rep. **65**, 389–394.

Mazurek, B., Olze, H., Haupt, H., and Szczepek, A. J. (**2010**). "The more the worse: The grade of noise-induced hearing loss associates with the severity of tinnitus," Int. J. Environ. Res. Public Health **7**, 3071–3079.

Mehrparvar, A. H., Mirmohammadi, S., Ghoreyshi, A., Mollasadeghi, A., and Loukzadeh, Z. (**2011**). "High-frequency audiometry: A means for early diagnosis of noise-induced hearing loss," Noise Heath **13**, 402–406.

Melamed, S., Froom, P., Kristal-Boneh, E., Gofer, D., and Ribak, J. (**1997**). "Industrial noise exposure, noise annoyance, and serum lipid levels in blue-collar workers—The CORDIS study," Arch. Environ. Health **52**, 292–298.

Melamed, S., Luz, J., and Green, M. S. (**1992**). "Noise exposure, noise annoyance and their relation to psychological distress, accident and sickness absence among blue-collar workers—The Cordis Study," Isr. J. Med. Sci. **28**, 629–635.

Middendorf, P. J. (**2004**). "Surveillance of occupational noise exposures using OSHA's Integrated Management Information System," Am. J. Ind. Med. **46**, 492–504.

Mills, J. H. (**1975**). "Noise and children: A review of literature," J. Acoust. Soc. Am. **58**, 767–779.

Ministry of Health and State Administration of Work Safety (**2007**). *Occupational Exposure Limits for Hazardous Agents in the Workplace Part 2: Physical Agents* (Ministry of Health and State Administration of Work Safety, Beijing, China).

Mirza, R., Kirchner, D. B., Dobie, R. A., and Crawford, J. (**2018**). "Occupational noise-induced hearing loss," J. Occup. Environ. Med. **60**, e498–e501.

Morata, T. C., Themann, C. L., Randolph, R. F., Verbsky, B. L., Byrne, D. C., and Reeves, E. R. (**2005**). "Working in noise with a hearing loss: Perceptions from workers, supervisors, and hearing conservation program managers," Ear Hear. **26**, 529–545.

Murphy, E., and King, E. A. (**2016**). "Testing the accuracy of smartphones and sound level meter applications for measuring environmental noise," Appl. Acoust. **106**, 16–22.

Murphy, W. J., and Kardous, C. (**2012**). "A case for using A-weighted equivalent energy as a damage risk criterion for impulse noise exposure," EPHB Report No. 350-11a, EPHB, Cincinnati, OH.

National Institutes of Health (**2019**). "Noisy planet," https://www.noisyplanet.nidcd.nih.gov/ (Last viewed: February 22, 2019).

Neitzel, R. L., and Fligor, J. B. (**2019**). "Risk of noise-induced hearing loss due to recreational sound: Review and recommendations," J. Acoust. Soc. Am. **146**, 3911–3921.

Neitzel, R. L., Swinburn, T. K., Hammer, M. S., and Eisenberg, D. (**2017**). "Economic impact of hearing loss and reduction of noise-induced hearing loss in the United States," J. Speech Lang. Hear. Res. **60**, 182–189.

NIOSH (**1998**). *Criteria for a Recommended Standard Occupational Noise Exposure Revised Criteria 1998* (National Institutes of Occupational Safety and Health, Cincinnati, OH).

Niskar, A. S., Kiezak, S., Holmes, A., Esteban, E., Rubin, C., and Brody, D. (**2001**). "Estimated prevalence of noise-induced hearing threshold shifts

among children 6 to 19 years of age: The third national health and nutrition examination survey, 1988–1994, United States," Pediatrics **108**, 40–43.
Occupational Safety and Health Service (**2002**). *Approved Code of Practice for the Management of Noise in the Workplace* (Occupational Safety and Health Service, New Zealand).
OSHA (**2010**). *Occupational Noise Exposure* (OSHA, Washington, DC), pp. 211–224.
Picard, M., Girard, S. A., Simard, M., Larocque, R., Leroux, T., and Turcotte, F. (**2008**). "Association of work-related accidents with noise exposure in the workplace and noise-induced hearing loss based on the experience of some 240,000 person-years of observation," Accid. Anal. Prev. **40**, 1644–1652.
Portnuff, C. (**2016**). "Reducing the risk of music-induced hearing loss from overuse of portable listening devices: Understanding the problems and establishing strategies for improving awareness in adolescents," Adolesc. Health Med. Ther. **7**, 27–35.
Portnuff, C. D. F., Fligor, B. J., and Arehart, K. H. (**2011**). "Teenage use of portable listening devices: A hazard to hearing?," J. Am. Acad. Audiol. **22**, 663–677.
Price, G. (**1981**). "Implications of a critical level in the ear for assessment noise hazard at high intensities," J. Acoust. Soc. Am. **69**, 171–177.
Rabinowitz, P. M. (**2010**). "Hearing loss and personal music players," BMJ **341**, 57–58.
Rabinowitz, P. M., Slade, M. D., Galusha, D., Dixon-Ernst, C., and Cullen, M. R. (**2006**). "Trends in the prevalence of hearing loss among young adults entering an industrial workforce 1985 to 2004," Ear Hear. **27**, 369–375.
Ramazzini, B. (**1713**). "Coppersmiths," in *Rammazini Morbis Artificum Diatriba* (*Diseases Work*), 1st ed., edited by W. Wright (University of Chicago Press, Chicago, IL).
Roberts, B., Kardous, C., and Neitzel, R. L. (**2016**). "Improving the accuracy of smart devices to measure noise exposure," J. Occup. Environ. Hyg. **13**, 840–846.
Roberts, B., Sun, K., and Neitzel, R. L. (**2017**). "What can 35 years and over 700,000 measurements tell us about noise exposure in the mining industry?," Int. J. Audiol. **56**, 4–12.
Rosing, S. N., Schmidt, J. H., Wedderkopp, N., and Baguley, D. M. (**2016**). "Prevalence of tinnitus and hyperacusis in children and adolescents: A systematic review," BMJ Open **6**, e010596.
Seixas, N. S., Neitzel, R., Stover, B., Sheppard, L., Feeney, P., Mills, D., and Kujawa, S. (**2012**). "10-year prospective study of noise exposure and hearing damage among construction workers," Occup. Environ. Med. **69**, 643–650.
Stern, F. B. (**2003**). "Mortality among chrome leather tannery workers: An update," Am. J. Ind. Med. **44**, 197–206.
Su, B., and Chan, D. (**2017**). "Prevalence of hearing loss in US children and adolescents findings from NHANES 1988-2010," JAMA Otolaryngol. Head Neck Surg. **143**, 920–927.
Suter, A. H. (**1988**). "The development of federal noise standards and damage risk criteria," in *Hearing Conservation in Industry, Schools, and the Military* (Pearson Allyn & Bacon, Boston, MA), pp. 45–66.
Suter, A. H. (**1992**). *The Relationship of the Exchange Rate to Noise-Induced Hearing Loss* (The National Institute for Occupational Safety and Health, Cincinnati, OH), pp. 1–58.
Suter, A. H. (**2003**). "Standards and regulations," in *The Noise Manual*, 5th ed., edited by E. Berger, L. Royster, J. Royster, D. Driscoll, and M. Layne (American Industrial Hygiene Association, Fairfax, VA), pp. 639–668.
Talbott, E. O., Gibson, L. B., Burks, A., Engberg, R., and McHugh, K. P. (**1999**). "Evidence for a dose-response relationship between occupational noise and blood pressure," Arch. Environ. Health **54**, 71–78.
Tharpe, A. M., Sladen, D. P., Dodd-Murphy, J., and Boney, S. J. (**2009**). "Minimal hearing loss in children: Minimal but not inconsequential," Semin. Hear. **30**, 80–93.
U.S. Department of Defense (**2015**). *Design Criteria Standard: Noise Limits MIL-STD-1474E* (USDOE, Washington, DC).
Virkkunen, H., Kauppinen, T., and Tenkanen, L. (**2005**). "Long-term effect of occupational noise on the risk of coronary heart disease," Scand. J. Work. Environ. Health **31**, 291–299.
Walter Reed Army Institute of Research (**2017**). "Acession Medical Standards Analysis & Research Activity 2016 Annual Report," http://www.amsara.amedd.army.mil/Documents/AMSARA_2016Report/AMSARAAR2016.pdf (Last viewed January 15, 2018).
Ward, W. D., Royster, J., and Royster, L. (**2003**). "Auditory and nonauditory effects of noise," in *Noise Management*, 5th ed., edited by E. H. Berger, L. Royster, J. Royster, D. Driscoll, and M. Lane (American Industrial Hygiene Association, Fairfax, VA), pp. 123–147.
WHO (**2008**). *Part 4: Burden of Disease: DALYs* (WHO, Geneva, Switzerland).
WHO (**2017**). "Make listening safe," http://www.who.int/pbd/deafness/activities/MLS_Brochure_English_lowres_for_web.pdf (Last viewed January 15, 2018).
Williams, W., Carter, L., and Seeto, M. (**2015**). "Pure tone hearing thresholds and leisure noise: Is there a relationship?," Noise Health **17**, 358–363.
Yong, J. S.-E., and Wang, D.-Y. (**2015**). "Impact of noise on hearing in the military," Mil. Med. Res. **2**, 6.
Zhao, Y. M., Zhang, S. Z., Selvin, S., and Spear, R. C. (**1991**). "A dose response relation for noise induced hypertension," Occup. Environ. Med. **48**, 179–184.