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

Make Listening Safe WHO

This document presents a review of existing evidence on risk of noise induced hearing loss due to exposure to sounds in recreational settings, with respect to children. The evidence was used to stimulate discussion for determination of exposure limits (in children) to be applied to standards for personal audio devices. The review has been undertaken by Dr Benjamin Roberts under the supervision of Dr Richard Neitzel, in collaboration with WHO. The document has been reviewed by members of WHO expert group on exposure limits for NIHL in recreational settings.

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Authors:
Dr Benjamin Roberts
Dr Richard Neitzel
Reviewed by:
Dr Brian Fligor
Dr Ian Wiggins
Dr Peter Thorne

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Definitions and Acronyms

Acceptable risk: The risk of NIHL deemed acceptable after accounting for scientific, health, and political considerations.

Child: Any human age 18 or below

dBA: Sound pressure level measured with the A-weighting network. Used to measure noise levels (except impulse noise) in occupational and environmental settings.

Exchange Rate (ER): A value (in dB) that can be added or subtracted to determine the allowable exposure time at a certain level of noise. For example, a 3 dB ER allows the doubling of exposure time for every 3 dB decrease in sound level or a halving in exposure time for each 3 dB increase in sound level. Typically, a 3 dB ER is used but some organizations or jurisdictions still utilize the 5 dB ER.

HTL: Hearing threshold level at a specific audiometric frequency,

L_{AVG}: Average noise level (in dBA), measured using the 5 dB ER.

L_{EQ}: Equivalent continuous average noise level (in dBA), measured using the 3 dB ER.

L_{EQ24}: Equivalent continuous average noise level (in dBA), normalized to a 24-hour exposure.

L_{EX}: Equivalent continuous average noise level (in dBA), normalized to an 8-hour exposure.

Material hearing impairment: A NIHL that exceeds 25 dB averaged across the 1, 2, 3, and 4 kHz audiometric frequencies in both ears.

NIHL: Noise-induced hearing loss, a permanent worsening in HTLs with a characteristic reduction in hearing sensitivity at the 3,4, and 6 kHz frequencies with relatively better hearing sensitivity at the 2 and 8 kHz frequency compared to pre-noise exposure thresholds.

Noise-induced permanent threshold shift (NIPTS): Synonymous with NIHL.

Noise-induced temporary threshold shift: NIHL that temporarily occurs after exposure to high levels of noise and recovers to pre-exposure thresholds.

Noise-induced tinnitus: Ringing or buzzing in the ears that can be either temporary or permanent following exposure to high levels of noise.

Non-occupational noise: Noise that occurs outside the workplace that an individual does not intentionally expose themselves to.

Occupational noise: Noise that is present in the workplace.

Recreational noise: Noise that an individual intentionally exposes themselves to as a part of recreational activity.

Executive Summary

This Report was prepared to address the following three questions posed by the WHO:

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?

3) What is an appropriate evidenced-based noise exposure limit for children in recreational settings?

Question 1: Occupational exposure limits are developed based on economic, technical, and political feasibility and are not purely health-based. Occupational exposure limits allow for a certain “acceptable” level of NIHL after a standard working lifetime and were not designed to consider vulnerable populations such as children. In addition, the duration and frequency of recreational noise exposure may differ greatly from that of occupational noise, making it inappropriate to simply adopt occupational exposure limits as limits for recreational noise.

Question 2: There are very few recommended exposure limits for recreational noise exposure, thus both environmental and recreational exposure limits were considered. The United States Environmental Protection Agency (EPA) and WHO have suggested exposure limits for the general environment and certain recreational activities, but these exposure limits were not specific to children and often did not include the estimated risk of NIHL at the recommended exposure levels. While these recommended exposure limits are more protective than occupational limits, and thus more suitable for use in vulnerable population groups, there is limited evidence to support their use for children.

Question 3: The WHO does not specify what is the acceptable risk of hearing loss in children. Therefore, this report assumed that the most appropriate exposure limit for children recreational noise 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 International Organization for Standardization (ISO) 1999:2013 model for predicting hearing loss, it was estimated that noise exposure equivalent to an 8-hour L_{EX} of 82 dBA would result in about 4.2 dB or less of hearing loss in 99 percent of children after 18 years of exposure. To further ensure that the risk of hearing loss in children is reduced, the L_{EX} was reduced to 80 dBA which is estimated to result in approximately 2.1 dB or less of hearing loss in 99 percent of children after 18 years of exposure. Previous reviews of the literature have indicated that recreational noise exposure often exceeds these levels, and that children may be at risk of developing NIHL prior to their entry to the workforce.

Background and Significance

Noise is by far one of the most common environmental exposure 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 (Berger et al, 2003; Berglund et al, 1999). Some of the earliest antecedal evidence of the effects of hazardous noise exposure were observed in the workplace where it was recognized that certain professions suffered from hearing loss (Roosa, 1885). As the world became more industrialized it became almost universally accepted that exposure to high levels of noise in the workplace would lead to hearing loss. As the 20^{th} century progressed the field of occupational health matured resulting in the promulgation of regulations limiting noise levels in the workplace (Suter, 2004; Kerr, 2017). While occupational noise exposure, at least in industrialized countries, have slightly decreased or at least leveled out, the same cannot be said for non-occupational and recreational noise (Cheng et al, 2017; Middendorf, 2004; Roberts et al, 2016b). A report published by the World Health Organization (WHO) in 2011 noted that "at least one million healthy life years are lost every year from traffic related noise in the western part of Europe" (WHO, 2011). While comparative estimates are not available for other locations, the report from the WHO illustrates the magnitude of the problem of environmental noise.

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 (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 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 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 noise may increase in the future (WHO, 2017).

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 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 have focused on the general population, and are not specifically intended for children. To specifically protect children from 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.

How Noise is Assessed

Two different types of devices are typically used to measure noise exposure. The first is a sound level meter (SLM). These devices can vary from very simple devices that only provide an instantaneous measure of noise levels to very sophisticated instruments capable of data logging measurements over time and providing simple statistical measures. SLMs are often too cumbersome for an individual to wear or carry for an extended period of time. Because of this noise dosimeters are often used to measure noise levels over extended durations (e.g., hours to days). There are two classifications for field-applicable SLMs and dosimeters: Type 1 and Type 2. Type 1 are precision instruments that are often used to make measurements in laboratory settings while Type 2 are typically used to make measurements in the field. Recently, researchers have begun to use applications (apps) on smart devices (phones, tablets, etc.) to measure noise exposure in a variety of occupational and environmental settings (Nast et al, 2014; Murphy & King, 2016; Roberts & Neitzel, 2017). While these devices are cheap and widely available, the model of the device, app used, and microphone selection can drastically impact the accuracy of measurements made with these devices making them useful only when they are properly configured and used, and when absolute accuracy is not critical (Roberts et al, 2016a; Kardous & Shaw, 2014; Kardous & Shaw, 2016; Roberts & Neitzel, 2017).

The microphones in SLMs, dosimeters, and smart devices measure sound pressure levels in pascals (Pa). However, because the human ear can detect sounds from 0.00002 (20 µPa) to 20 Pa the logarithmic decibel (dB) notation is used to measure noise levels (OSHA, 2013). Measurements are made across a large frequency range (typically 20-20,000 hertz, Hz). However Fletcher and Munson recognized that humans are more sensitive to certain frequencies of noise than others and accordingly developed the A-weighted decibel (dBA), which is now used as the unit of measure for virtually all noise standards and for predicting noise-induced hearing loss (NIHL) (Fletcher & Munson, 1933). While noise levels can be measured at a single point in time, all occupational and environmental noise regulations rely on noise levels normalized over certain periods of time (8 hours in occupational settings, or generally 24 hours for environmental noise) to assess compliance with applicable regulations and to determine the risk of NIHL.

In addition to continuous noise exposure, impulse noise exposure can also lead to NIHL. Impulse noise is a very sudden and intense burst of noise that is most often caused by explosions or high-speed, energetic impacts (Berglund et al, 1999). The unweighted (dB) or C-weighted (dBC) decibel has been recommended for use in measuring impulse or peak noise (Berger et al, 2003; ACGIH, 2017). While most exposures to occasional impulse noise averaged over a workday or 24-hour period would not be expected to cause any hearing damage, the amount of energy emitted from impulse noise can potentially cause acute acoustical trauma (OSHA, 2013), particularly when levels exceed 130-140 dB or dBC.

Overview of the Health Effects of Noise Exposure

Noise exposure is most commonly associated with an increased risk of noise-induced hearing loss (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.

Hearing Loss

Hearing loss can be either be conductive, where sound waves are attenuated or altered when passing through the outer and middle ear, or sensorineural, where damage has occurred in the cochlea (inner ear) or the auditory nerve that connects the cochlea and the auditory processing area of the brain. Noise exposure primarily causes a sensorineural hearing loss which is both completely preventable and irreversible (Berger et al, 2003). 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 (Kirchner et al, 2012). This is due mainly to the fact that the structure of the outer and middle ear amplifies sounds in the 2-4 kHz range by as much as 15 dB (Schmiedt, 1984),. 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 (Berger 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.

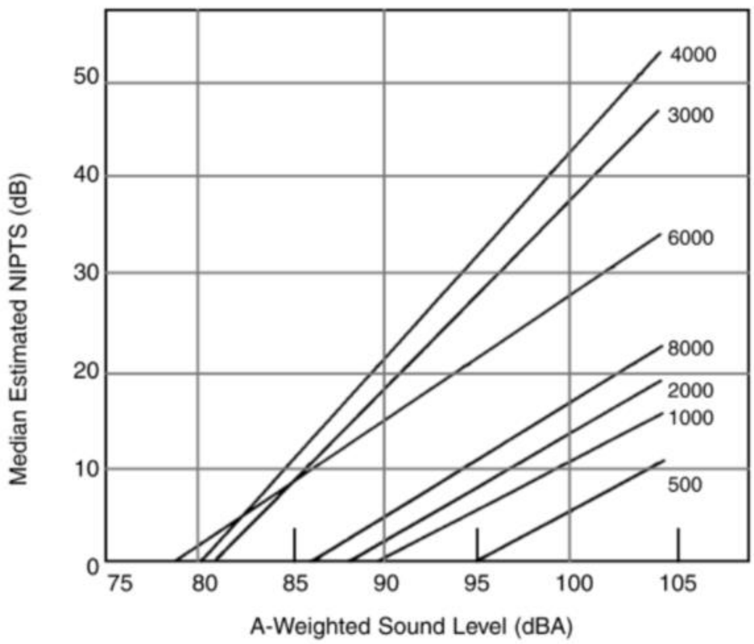

Figure 1. Estimated hearing loss at different audiometric frequencies from various average levels of occupational exposure to noise (Reprinted from the Noise Manual 5th Edition) (Berger et al, 2003).

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 increase risk of occupational injury (Picard et al, 2008b; Morata et al, 2005; Cantley et al, 2014). In addition, the interference in communication and reduced ability to perceive one's surrounding environment from hearing loss (from either noise or ageing) can lead to social isolation and be detrimental to a person's mental health (Noble, 2009; Leather et al, 2003). These issues may increase in severity as hearing loss progresses.

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. In a recent systematic review, 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. Tinnitus can be temporary or permanent, and temporary tinnitus can serve as a warning that a person was exposed to hazardous levels of noise (Mazurek et al, 2010).

The WHO estimated that adult onset hearing loss is responsible for 27.4 million disability adjusted life years (DALYs) worldwide (WHO, 2008a). The economic costs of NIHL are significant with one study estimating that NIHL costs the US economy between $58 and $152 billion in direct and indirect costs annually (Neitzel et al, 2017).

Special Considerations for Hearing Loss in Children

As it 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 (WHO, 2008b; Krug, 2014; 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. For example, a study of grade five students in Malaysia found that poor academic performance was significantly ($p < 0.001$) associated with a mild hearing loss (20-39 dB), although 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 this study 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 (Flexer, 2004; Elliott, 1979; Mills, 1975). It is also important to consider that NIHL is irreversible and that the NIHL developed early in life will likely get progressively worse, as the individual is further exposed to noise, and will follow the child through primary school, university, and in to the workplace where hazardous levels of noise may also be present.

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 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 ABR and DPOAE compared to mice who were exposed later in life (Kujawa & 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 after exposure has ceased.

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 1,455 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 (Talbott et al, 1999; Zhao et al, 1991; Chang et al, 2007). 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 (Melamed et al, 1992; Leather et al, 2003). In the general environment 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 (Evans et al, 2001; Evans, 2006; Berger et al, 2003; Berrglund & Lindvall, 1995; EPA, 1973). However, very little research has been conducted examining the non-auditory effects of noise exposure on except for the effect of noise on academic performance 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).

Objectives (from WHO scope of work)

The objective of this report is to review the peer reviewed literature and current regulations regarding the effects of recreational noise exposure on children. Specifically, the following research questions will be answered:

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?

3) What is an appropriate evidenced-based noise exposure limit for children in recreational settings?

Research Questions

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

Occupational Noise Exposure

Occupational noise exposure is one of the most common occupational hazards with an estimated 22 million workers in the US exposed to hazardous workplace noise (Tak et al, 2009). An analysis conducted by Masterson et al. found that the prevalence of hearing loss in the US from 2006 to 2010 ranged from about 12 to 25% depending on the industry (Masterson et al, 2016). NIHL significantly decreases an individual's quality of life by making communication and social interactions more difficult and potentially limiting future economic potential (Basner et al, 2014; Neitzel et al, 2017). In addition, occupational noise exposure has also been associated with increased risk of injury and reduced work performance (Barreto et al, 1997; Picard et al, 2008a; Noweir, 1984) . Despite economic and health costs of occupational noise exposure many occupations still expose workers to hazardous levels of noise (Berger et al, 2003; Berglund et al, 1999; Middendorf, 2004; Roberts et al, 2016b; Cheng et al, 2017).

Numerous occupational exposure limits for noise have been established by governmental agencies and non-governmental groups (Berger et al, 2003). Currently the United States Occupational Safety and Health Administration (OSHA) enforces a permissible exposure limit (PEL) of 90 dBA, as an 8-hour time weighted average (8-hr TWA), with a 5 dB time-intensity exchange rate (ER) (i.e. the L_{AVG}) (OSHA, 1983). 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 (Berger et al, 2003). This is similar to the recommended 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 (2003) sets an eight hour exposure limit (i.e. the L_{EX}) 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 of the Council, 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 1 provides a summary of allowable exposure times according to different governmental agencies and consensus groups.

		Allowable exposure (dBA) for corresponding time period					
Organization		**16 hours**	**8 hours**	**4 hours**	**2 hours**	**1 hour**	**Peak[a]**
EU							
	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
ACGIH	Threshold Limit Value	88	85	88	91	94	140
NIOSH (US)	Recommended Exposure Limit	88	85	88	91	94	140
OSHA (US)							
	Permissible Exposure Limit	95	90	95	100	105	140
	Action Level	90	85	90	95	100	
Canada (Federal)[b]	Permitted Exposure Level	84	87	90	93	96	
Australia	Permitted Exposure Limit	82	85	88	91	94	140
New Zealand	Permissible Exposure Limit	82	85	88	91	94	140
China	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] Exposure limits vary based on the province.

Table 1. Allowable exposure times for occupational exposure to noise.

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 (Suter, 1988; Suter, 1992; NIOSH, 1998). Figure 2 illustrates the magnitude of the difference in allowable exposure time between the criteria set by OSHA and the criteria set by NIOSH. It is estimated that the excess risk of developing NIHL, (>25 dB of hearing loss summed across the 1,2,3, and 4 kHz frequencies) is 25% when complying with the occupational exposure limit promulgated by OSHA compared to 8% when following the recommended exposure limit put forth by NIOSH and most governments (NIOSH, 1998). While studies of hearing loss risk have been conducted using both the OSHA L_{AVG} and the L_{EQ} metric, the general consensus in the scientific community is that the L_{EQ} is superior to the L_{AVG} in predicting NIHL and therefore no further discussion of the L_{AVG} is warranted (ISO, 2013; Suter, 1988; Suter, 1992) .

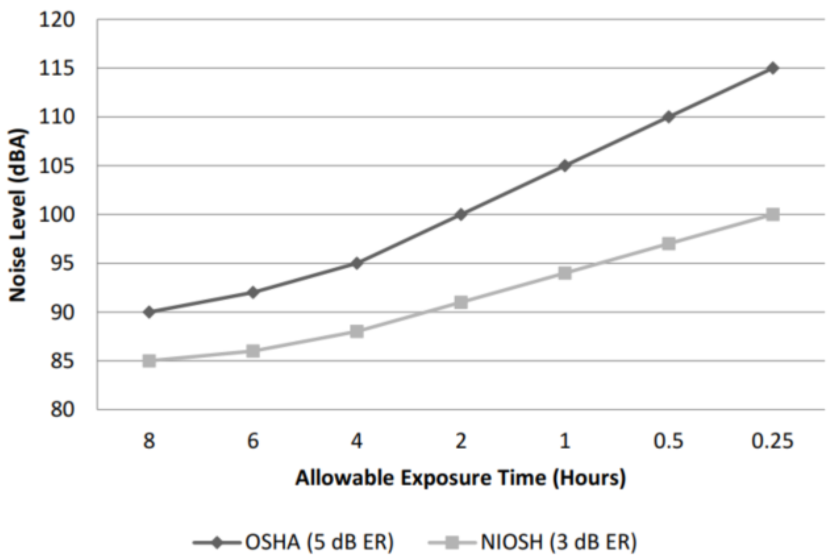

Figure 2. Allowable exposure time using the OSHA and NIOSH noise criteria.

Applicability of Current Occupational Exposure Limits for Noise to Children Recreational Noise Exposure

The L_{EQ} can be calculated over any period of time, typically 8 hours for occupational noise exposure (the L_{EX} described above), and 24 hours for environmental noise exposure (i.e., the $L_{EQ(24)}$). Exposures of equivalent risk of NIHL are determined by doubling or halving the exposure time for each 3 dB subtracted from or added to the L_{EQ} (NIOSH, 1998) – hence the term "time-intensity exchange rate." The allowable exposure time for a given level of exposure can also be calculated using Equation 1, where T_i is the allowable exposure time for noise exposure L_i, using criterion time T_C, criterion level L_C, and ER is exchange rate of 3 dB. It is mathematically possible to calculate the allowable exposure duration from as brief a period as one second to a full 24-hour 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 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).

$$T_i = \frac{T_C}{2^{\frac{L_i - L_C}{ER}}}$$

Equation 1.

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 exposure 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 limits from NIOSH, ACGIH, and the EU allow for a small, but still significant percentage of workers to develop hearing loss (NIOSH, 1998; ISO, 2013). Finally, occupational exposure limits are derived based on the assumption that a worker will be exposed of a normal working lifetime (i.e. about 40 hours a week for 40 years), while exposure to recreational noise likely extends over a lifetime and potentially occurs more than 40 hours each week (Portnuff et al, 2011; Gopal, 2017; Neitzel & Fligor, 2017).

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 the regulations regarding occupational noise exposure also specify levels at which a worker must be given hearing protection, rotated out of a job, or enrolled in a hearing conservation program (HCP) (ACGIH, 2017; Berger et al, 2003; European Parliament and of the Council, 2003; OSHA, 1983). However, because recreational noise is something that individuals willingly expose themselves to, as part of the recreational activity, 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. In addition, occupational exposure limits were developed for adults who may have physiologically different auditory systems than children, which may modify the risk of developing hearing loss as they age (Abdala & Keefe, 2012; Kujawa & 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 recreational noise.**

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

Current Non-Occupational Exposure Limits for Noise

The US EPA and the WHO have both recommended exposure limits for environmental noise. The EPA sets a 24-hour ($L_{EQ(24)}$) of 70 dBA using the 3 dB ER in order to prevent NIHL (EPA, 1974). This is equivalent to an L_{EX} of 75 dBA assuming that any noise exposure outside of that 8-hours is below 60 dBA. This limit was designed to protect 96 percent of the general population from hearing loss greater than 5 dB at the 4 kHz audiometric frequency. The EPA 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 at an 80, 85, and 90 dBA L_{EX}. 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 al, 1999).

Unlike the EPA, in its guidelines for community noise the WHO specifically 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 a year. 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.

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-hour 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 & Fligor, 2017). 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. Recommended exposure limits for environmental and recreational noise are summarized in Table 2.

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

Table 2. Environmental and recreational noise exposure limits.

Applicability of Existing Non-Occupational Exposure Limits for Noise to Children

Unlike occupational noise regulations, environmental noise regulations seek to protect almost all individuals from hearing damage. The WHO specifically suggests limits for recreational noise exposure based on the risk of hearing loss. However, in its 1999 guidelines for community noise it 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 & Fligor, 2017). 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.

What are the appropriate evidence-based exposure limits for children (in recreational settings)?

Recommended Exposure Limit for Children Exposure to Recreational Noise

Establishing a recommended exposure limit for children in recreational settings is inherently a political, economic, and ethical issue. The first issue that must be resolved is what (if any) level of NIHL is deemed acceptable in children. The WHO has stated that hearing loss greater than 10 dB averaged over the 2 and 4 kHz audiometric thresholds in both ears could result in a hearing and communication handicap (Berglund et al, 1999). Other organizations have established different levels of acceptable hearing loss: for example, NIOSH considers a NIHL greater than 15 dB at the 0.5, 1,2,3,4, or 6, kHz frequencies to be significant (NIOSH, 1998). OSHA requires reporting of hearing loss when it exceeds 25 dB averaged at the 2, 3, and 4 kHz in the same ear (OSHA, 1983). The simplest way to address this issue would be to adopt a limit that is associated with zero excess risk of developing NIHL. A recent WHO report identified a L_{EX} of 75 dBA which is equivalent to a 70 dBA $L_{EQ(24)}$ (Neitzel & Fligor, 2017). From a purely health prospective, this exposure limit for recreational noise is recommended given the previously described deleterious effects of hearing loss especially in children.

While elimination of 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 will seek to 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 generally not noticeable, 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 allows for the estimation of hearing threshold levels when accounting for aging and noise exposure in a highly screened ontologically normal population. However, 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 age in children, but 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 Equation 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 hour working day, and L_0 represents the frequency dependent sound level at which effect on hearing is negligible.

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

Equation 2.

The 99th percentile can then be calculated using equation 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 method (ISO, 2013).

$$N_{99} = N_{50} + k \times d_u$$

Equation 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 Figure 3. Based on the results of the model, 99 percent 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 noticeable or significant (EPA, 1974).

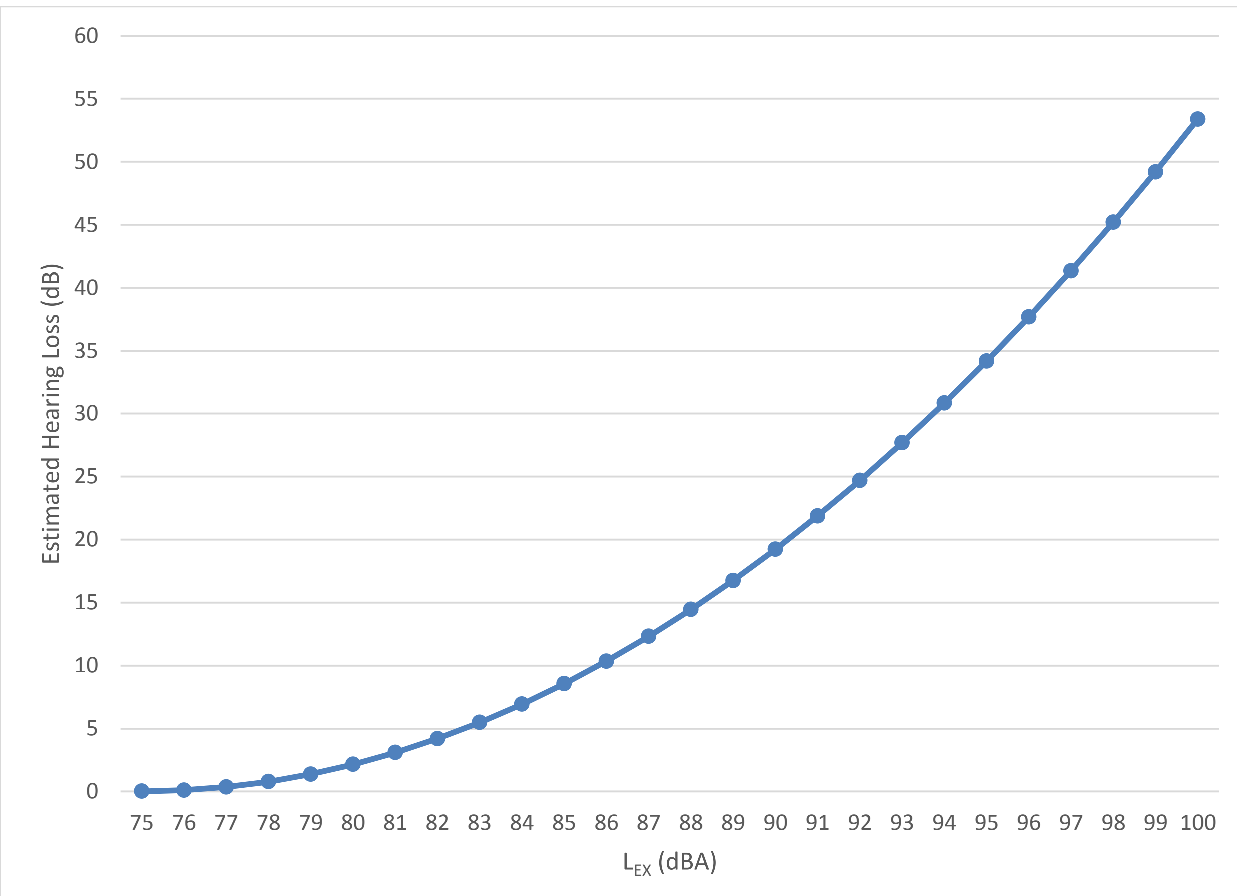

Figure 3. Estimated levels of hearing loss for the 99th percentile of the population at the 4kHz frequency after 18 years of exposure.

If it could be assumed that recreational noise exposure only lasted during childhood, and that exposure from the workplace and general environment were insignificant (i.e. below 60 dBA) 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 predicted by 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 (Masterson et al, 2016). 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 (Berger et al, 2003). However, because the 82 dBA exposure limit was derived using conservative assumptions, and because the difference in estimated hearing loss between 79 and 80 dBA is miniscule (approximately 0.75 dB) **the recommended exposure limit for recreational noise for children is 80 dBA as a 8-hour L_{EX}.**

This exposure limit is equivalent to the eight hour lower exposure action level for workplaces in the EU (European Parliament and of the Council, 2003) and is slightly more protective than the 83 dBA exposure limit recommended by Neitzel and Fligor in 2017 for exposure to recreational noise in the general population (Neitzel & Fligor, 2017). The allowable exposure duration at various levels of noise can be determined by using figure 4, which was calculated using equation 1.

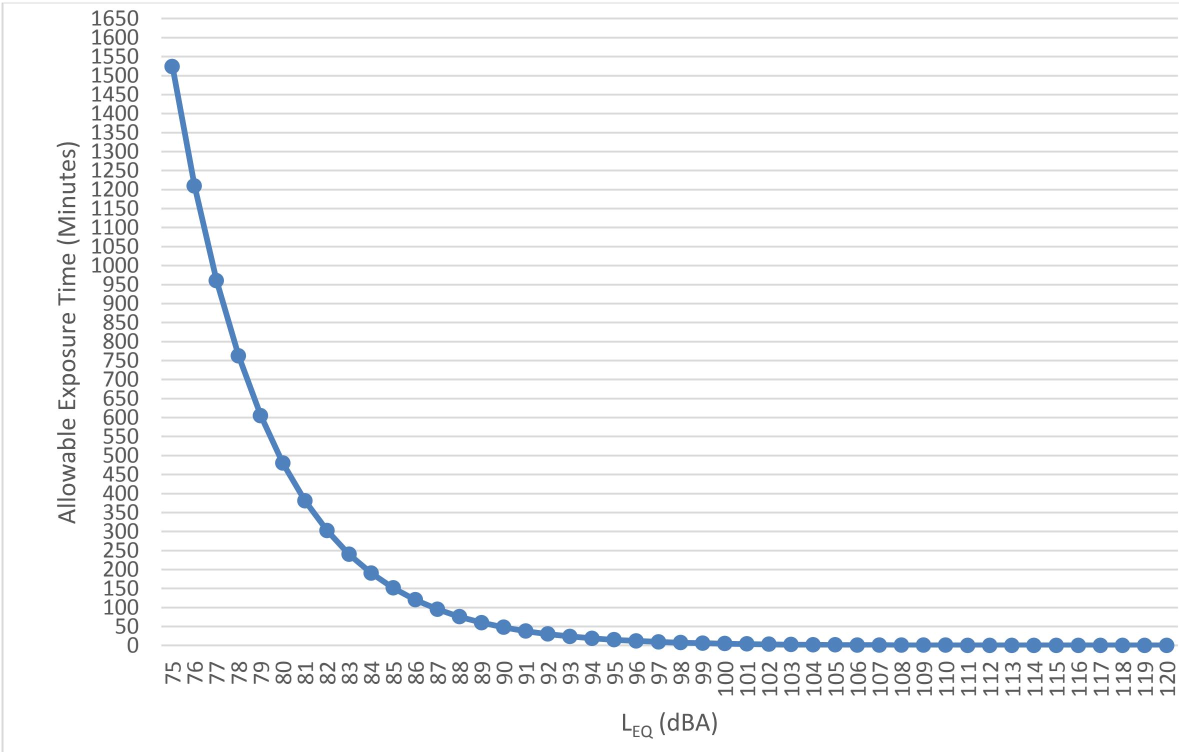

Figure 4. Allowable exposure time (minutes) at various levels of noise exposure.

A limit for impulse noise cannot be directly derived using the ISO 1999 standard. However, as can be seen in Figure 4, allowable exposure times at noise levels greater than 100 dBA are on the scale of seconds, suggesting that a *de facto* limit of 100 dBA for impulse noise for children may be appropriate. When exposure to impulse noise is expected (e.g. firearms, explosives, etc.) double hearing protection (i.e. ear plugs and earmuffs) should be utilized to prevent any risk to hearing loss.

A recent review by Jiang et al. noted that the average 8-hour L_{EX} for noise exposure from personal listening 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 (Jiang et al, 2016). 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 hours per day, with a range of 0.5 to 5.75 per day (Portnuff et al, 2011). In addition to PLDs, other sources of recreational noise exposure include attending sporting events, concerts, and other noisy activities that can expose an individual to an L_{EX} ranging from 79-130 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 frequency are 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 for the rates of hearing loss observed in young adults entering the workforce (Seixas et al, 2012; Rabinowitz et al, 2006).

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 adequately quantified 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 of hearing loss be found unacceptably high, an exposure limit of 75 dBA would be recommended for maximum protection.**

Several uncertainties in deriving the recommended exposure limit of 80 dBA were considered 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 recreational noise consistently from its birth until age 18. While the literature has suggested that the duration of recreational noise exposure can vary, it is unlikely that a child will immediately seek out recreational noise immediately after its birth. However, it is 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). There is a need to perform a meta-analysis of the literature to better understand the frequency, duration, and intensity at which children engage with various forms of noisy recreational activity. 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. 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 contemporary occupational exposure limits.

Uncertainty also arises because the ISO 1999 model is intended for an otologically normal adult (> 18 years) population (Williams et al, 2015; ISO, 2013). However, the extrapolation of the model to children is necessary because there is not currently a hearing loss model specific to children. However, it is expected that the immediate damage to hearing threshold levels from hazardous noise exposure would affect children in the same manner as adults. Additionally, the recommended exposure limit was chosen to limit NIHL to below 5 dB in the 99^{th} percentile of the population, which is in the extreme right tail of the normal distribution and as a result the model has less experimental data (ISO, 2013). However, the results of a sensitivity analysis using the ISO1999 model found that the difference in estimated hearing loss between the 95^{th} and 99^{th} percentile was less than 0.3 dB suggesting that using the 99^{th} as opposed to the 95^{th} percentile would not change the conclusions of this report.

The primary 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 what causes hearing loss (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 (Harrison & Kelly, 1989; Ando, 2001)

There has been an increased interest in measuring noise-induced changes in the auditory system other than loss of hearing sensitivity as measured in an audiogram. This is often referred to as “hidden hearing loss”. There is speculation that this type of hearing loss 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). Most of the current 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 & Liberman, 2009). However, this threshold for damage has not been identified in humans (Guest et al, 2017). 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. However, 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 & Liberman, 2015). Until a relationship between noise exposure and cochlear synapathy can be established, the incidence of tinnitus may serve as the more sensitive warning of early NIHL (Guest et al, 2017).

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 engages non-occupational activities that regularly exposes them to hazardous levels of noise then it would be expected that hearing loss would occur in excess of what is predicted by the model used to derive this exposure limit. In these events it is recommended that the child wear hearing protection, and reduce the intensity, duration, and frequency of their recreational noise exposure to avoid damage to their hearing.

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 significantly 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, still 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.

1. Use noise-reducing or noise-canceling headphones or earbuds when using PLDs. Jiang et al. noted in their review of noise exposure from PLDs that background noise levels were correlated ($r=.70$; $p< 0.05$) with higher listening levels on PLDs (Jiang et al, 2016). Noise canceling headphones help block noise from the general environment so that the listener does not have to increase the volume of their PLDs to overcome interference from background noise.
2. 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. There are specialized hearing protection devices available to protect the user from noise while not hampering the quality of the sound in these environments.
3. 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 SLM 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 & Celestina, 2017; Roberts et al, 2016a; Kardous & Shaw, 2016). It should be noted that there are several variables that influence the accuracy of these measurements, so an end user should only use these devices for general guidance and educational purposes.

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