DETERMINATION OF RISK OF NOISE-INDUCED HEARING LOSS DUE TO RECREATIONAL SOUND: REVIEW

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. The evidence will be used to stimulate discussion for determination of exposure limits to be applied to standards for personal audio devices. The review has been undertaken by Dr Richard Neitzel with inputs from Dr Brian Fligor, in collaboration with WHO.

February 2017

REVIEW: DETERMINATION OF RISK OF NOISE-INDUCED HEARING LOSS DUE TO RECREATIONAL SOUND

DEFINITIONS AND ACRONYMS

[Add more definitions as needed/desired, ideally to be drawn directly from ISO and IEC standards]

Acceptable Risk: the risk of NIHL determined to be acceptable after accounting for scientific, health, and political considerations, as well as respecting that individuals have autonomy and experience benefit from exposure to sound.

Damage-Risk Criteria, Risk Criteria: Archaic terms referring to the risk of noise-induced hearing loss (NIHL) presented by various levels of noise exposure. In this report these terms are replaced with several preferred contemporary terms: "dose-response relationship," "risk," or "exposure limit."

Decibels: (add definition from ISO)

Decibels, A-weighted (dBA): Decibels of sound pressure level measured using the A-weighting network; a level used to measure occupational and environmental noise exposures that reflects human hearing sensitivity across different hearing thresholds

Decibels, hearing level (dBHL): Decibels of hearing level; a level used to measure audiometric hearing threshold levels

ER (Exchange rate): the change in average noise level (in dB) that corresponds to a doubling or halving of allowable exposure time. As an example, a 3 dB exchange rate permits a doubling or halving of exposure duration for every 3 dB increase or decrease in average noise level, respectively, e.g., 8 hours of noise exposure permitted at 80 dBA, 4 hours at 83 dBA, 2 hours at 86 dBA, etc.

Excess risk: the risk of NIHL (i.e., hearing loss above that expected from non-noise sources, such as genetics, aging, etc) associated with a specific amount of exposure, typically in occupational settings.

HTL: Hearing Threshold Level at specific audiometric test frequencies, measured in dBHL

L_{EQ}: Equivalent continuous average noise level (dBA), measured using a 3 dB exchange rate

$L_{EX,8h}$: Equivalent continuous average noise level (dBA), measured using a 3 dB exchange rate, and normalized to an 8-hour exposure period; may also be referred to as an L_{A8hn}.

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

NIHL: Noise-induced hearing loss, defined as a permanent decrement in hearing threshold levels (HTLs), with a characteristic reduction of hearing sensitivity at the frequencies of 3, 4, and/or 6 kHz, and relatively better hearing sensitivity in surrounding frequencies (i.e., 2 or 8 kHz)

Noise: unwanted sound

Noise-induced Permanent Threshold Shift: Synonymous with permanent NIHL.

Noise-induced Temporary Threshold Shift: NIHL that results from exposure to noise but recovers after a sufficient time spent in low noise conditions.

Nonoccupational noise: Sound exposure that occurs outside of the employment setting, and is not regulated or otherwise under the jurisdiction of governmental occupational safety organizations.

Sound-induced Tinnitus: Perception of phantom sound in the ears or head that are either temporary or permanent, following excessive sound exposure.

Sound injury: Term typically used to refer to injurious exposure from a brief but intense sound, and therefore synonymous with acute hearing loss or acoustic trauma. Used less commonly to refer to NIHL resulting from chronic exposure.

SIHL: Sound-induced hearing loss, defined as a permanent decrement in hearing threshold levels (HTLs), with a characteristic reduction of hearing sensitivity at the frequencies of 3, 4, and/or 6 kHz, and relatively better hearing sensitivity in surrounding frequencies (i.e., 2 or 8 kHz)

Sound-induced Permanent Threshold Shift: Synonymous with permanent SIHL.

Sound-induced Temporary Threshold Shift: SIHL that results from exposure to noise but recovers after a sufficient time spent in low noise conditions.

PURPOSE OF THIS REPORT

This document comprises a review of peer-reviewed scientific literature addressing the issue of risk of sound-induced hearing loss (SIHL) due to exposures to recreational sound (in other words, exposures not considered to be unwanted, e.g., noise). The review was conducted to support efforts by the World Health Organization (WHO) Make Listening Safe campaign. The review, which is not intended to represent an exhaustive literature review, was conducted by Richard Neitzel, PhD, CIH, FAIHA™ from August-December 2016, with subsequent review and input from Brian Fligor, ScD, PASC in February 2017.

The specific goals of the review, as defined by WHO, were:

- To advise WHO on definitions relating to recreational SIHL.
- To guide WHO in establishing/adopting evidence-based risk exposure criteria for recreational SIHL.
- To ascertain the efficacy of these criteria, if required.

The overall question addressed by this review was:

1. Are existing exposure limits used for occupational noise exposure suitable for determination of risk due to recreational sound?

Specific sub-questions addressed in this review were:

2. What is the mechanism for determining exposure limits for occupational exposure?
3. What is the difference in nature of sound exposure in occupational and recreational settings?
4. What is the most appropriate exposure limit according to present understanding and knowledge? In other words, are the typical current occupational exposure limits of 85 dBA for 8 hours with a 3 dB time-intensity exchange rate the most suitable limits?

Each of these questions is addressed in a separate section of this review.

EXECUTIVE SUMMARY

This report was prepared to address the following question posed by WHO: are existing exposure limits used for occupational noise exposure suitable for determination of risk due to recreational sound?

Within this question lie **three sub-questions**, which represent the focus of this report:

5. What is the mechanism for determining exposure limits for occupational exposure?
6. What is the difference in nature of sound exposure in occupational and recreational settings?
7. What is the most appropriate exposure limit according to present understanding and knowledge?

Question 1: Occupational and nonoccupational exposure limits represent political compromises and are typically not solely evidence-based. The vast majority of nations and regulatory agencies around the globe have specified a 8-hour time-weighted exposure limit for occupational noise of 85 dBA using a 3 dB time-intensity exchange rate, i.e., an $L_{EX,8h}$. To completely eliminate the risk of any measurable noise-induced hearing loss in any exposed individual across audiometric frequencies of 0.5-6 kHz, the appropriate exposure limit would be a 24-hour equivalent continuous exposure level ($L_{EQ(24)}$) limit of 70 dBA with a time-intensity exchange rate of 3 dB, which is equivalent to an 8-hour $L_{EX,8h}$ exposure of 75 dBA (assuming that the average noise level for the remaining 16 hours of the day is 60 dBA or less). A limit of 75 dBA $L_{EQ(24)}$ (energetically equivalent to an 8-hour $L_{EX,8h}$ of 80 dBA) is expected to result in an excess risk of a material hearing impairment of less than 1% (i.e., < 1 out of 100 workers exposed at this level daily for 40 years would have a hearing impairment in excess of what would be expected from aging alone), and a change in median threshold levels 1, 2, 3 and 4 kHz of <5 dB. A limit of 80 dBA $L_{EQ(24)}$ (energetically equivalent to an 8-hour $L_{EX,8h}$ of 85 dBA) is expected to result in an excess risk of a material hearing impairment of 8% (i.e., 8 out of 100 workers exposed at this level daily for 40 years would have a hearing impairment from noise), and a change in median threshold levels 1, 2, 3 and 4 kHz of <10 dB

Question 2: The effects of occupational noise exposures on TTS may be worse than those of some types of energetically-equivalent music. However, the tremendous variation in types of music warrant the adoption of conservative exposure guidelines that presume exposure to the most harmful types of music, and this report therefore recommends that exposure limits developed for noise be considered applicable to music exposures. Furthermore, there is evidence that music listening patterns differ substantially from patterns of occupational noise exposure, and exposure durations are potentially substantially higher for music exposure. The broadly-accepted, energy-based assumptions regarding risk of hearing loss from noise exposures in international standards (ANSI 1996; ISO 2013) presume that varying temporal patterns of exposure do not influence risk of hearing loss. These standards assume a daily exposure duration of no more than 12 hours, which occurs infrequently with regards to occupational noise as well as to music exposures. Therefore, application of the existing ANSI and ISO models to prediction of hearing loss from music is considered appropriate, with the important caveat that these models are not intended to predict loss over durations greater than 40 years.

Question 3: Without a specified WHO definition of maximum acceptable noise-induced permanent threshold shift, it is not possible to determine the risk of individuals meeting or exceeding that definition following exposure to music, and in turn impossible to determine an acceptable level of risk of NIHL. Nevertheless, this review has concluded that the adoption of the most protective occupational noise exposure limit, European Union Directive 2003/10/EC (2003), i.e., the lower exposure action value of 80 dBA 8-hour $L_{EX,8h}$, which is energetically equivalent to recommendations from the US EPA and WHO for nonoccupational noise of 75 dBA $L_{EQ(24)}$ (EPA 1974; WHO 1999), is warranted for the purposes of minimizing risk for music-induced hearing loss in children and adults. Adoption of an 80 dBA 8-hour $L_{EX,8h}$ (i.e., 75 dBA 24-hour $L_{EQ(24)}$; 89 dBA 1-hour L_{EQ}) limit for exposure to music likely represents an optimal trade-off between being sufficiently protective and being onerous and/or technically or socially infeasible.

Alternative exposure limits might be considered appropriate, if the user of these guidelines wishes to establish greater restriction on exposure limits (and eliminate any risk for music-induced hearing loss) or lesser restriction on exposure limits (accepting higher risk for SIHL). To eliminate risk for music-induced hearing loss, an appropriate exposure limit is 75 dBA 8-hour $L_{EX,8h}$ (i.e., 70 dBA $L_{EQ(24)}$; 84 dBA 1-hour L_{EQ}). A lesser restriction on exposure limits, applicable to individuals willing to tolerate a small risk for a small degree of SIHL:, but still sufficiently protective of the vast majority of people exposed to nonoccupational music exposures is 85 dBA 8-hour $L_{EX,8h}$ (i.e., 80 dBA $L_{EQ(24)}$; 94 dBA 1-hour L_{EQ}). The latter exposure limit is consistent with workplace regulations for occupational noise in place in most countries in the world, and would be appropriate for individuals willing to accept a higher risk of SIHL..

Examples of individuals who may wish to eliminate any risk for music-induced hearing loss and adopt the most protective 75 dBA $L_{EX,8h}$ are:

(1) Young children or those not expected to have the autonomy to make informed personal health decisions;
(2) Persons with pre-existing hearing loss (NIHL, SIHL or from another cause) or pre-existing tinnitus;
(3) Persons who have a family history of NIHL or SIHL, or in whom there is reason to believe increased susceptibility to SIHL or sound-induced tinnitus (e.g., persons treated with ototoxic medications; persons exposed to chemicals that might potentiate the deleterious effects of noise).

QUESTION 1: WHAT IS THE MECHANISM FOR DETERMINING THE HEARING LOSS RISK FOR OCCUPATIONAL EXPOSURE?

1.1 Occupational Noise

Occupational noise exposure is one of the most frequent hazards present in the workplace; as many as 22.4 million workers are exposed to potentially hazardous levels of noise each day (Tak et al. 2009). Although regulations (OSHA; 2003) and recommended standards (NIOSH 1998; ACGIH 2006a) have been in place for decades, the prevalence of noise overexposures and NIHL remains high (Nelson et al. 2005; Daniell et al. 2006)[)]. NIHL is one of the most common occupational injuries in the United States and Europe, with workers in manufacturing, construction, and the military at especially high risk for hearing loss (Schneider 2005; NIOSH 2010; Masterson et al. 2014; Alamgir et al. 2016; Masterson et al. 2016). NIHL has a profound impact on affected individuals, substantially reducing quality of life and impairing social and occupational abilities and relationships (Sataloff and Sataloff 1996; Passchier-Vermeer and Passchier 2000). The WHO has previously noted that, unlike other environmental problems, which have been reduced over time through regulation, noise exposures appear to be increasing over time (WHO 1999).

Noise measurements made with the different metrics can result in divergent conclusions regarding NIHL risk, and the greater the variability, intermittency, or impulsiveness of a noise exposure profile, the greater the divergence between the metrics (Petrick et al. 1996; Neitzel et al. 1999). There is broad consensus among the scientific community that the best measure of the risk of NIHL presented by continuous exposure to levels of noise is decibels (dB) of sound pressure level measured using the so-called A-frequency weighting network (e.g., dBA). Note that for intense noise exposures (i.e., continuous exposures to noise greater than approximately 110 dB, or to brief sounds of roughly 120 dB or greater), a different weighting network (C-weighting) may be more appropriate. However, the vast majority of human epidemiological data collected with regards to NIHL have been measured using dBA, and this remains the metric of choice for virtually all assessments of occupational noise. Similarly, the scientific community generally agrees that the best metric for measuring average exposure to noise – likely the best predictor of NIHL risk from chronic exposure to noise – is the equivalent continuous average sound pressure level, or L_{EQ}. The L_{EQ} can be computed over any period of time desired; for occupational noise exposure, the period chosen is nearly always 8 hours, while for environmental noise exposure, the period chosen is often 24 hours. When the exposure period is normalized to exactly 8 hours, the L_{EQ} is referred to as $L_{EX,8h}$. To account for noise levels that vary over time, the L_{EQ} uses a 3 dB time-intensity exchange rate. That is, for every 3 dB change in the average exposure level, the allowable exposure duration is halved or doubled. So, for example, using a 3 dB exchange rate, a noise exposure of 85 dBA on average for 8 hours (i.e., an 85 dBA $L_{EX,8h}$) is considered to have identical risk of NIHL over time as an exposure of 88 dBA for 4 hours, 91 dBA for 2 hours, 94 dBA for 1 hour, and so on (NIOSH 1998).

There are a variety of occupational noise exposure limits in use around the world (**Table 1**). The American Conference of Governmental Industrial Hygienists (ACGIH) has set its Threshold Limit Value (TLV) for noise as an 85 A-weighted decibel (dBA) 8 hour-Time-Weighted Average using a 3 dB time-intensity exchange rate (e.g., an $L_{EX,8h}$)(ACGIH 2006b). This TLV was established to "…protect the median of the population against a NIHL exceeding 2 dB after 40 years of occupational exposure for the average of 0.5, 1, 2, and 3 kHz" and "will not protect all workers from the adverse effects of noise exposure." The damage expected from chronic exposures above the TLV is expected to be metabolic in nature, with cochlear processes serving as the target organ. The TLV also sets a peak exposure limit of 140 dBC, intended to protect against potential mechanical damage to the cochlea from high-level impulsive noise. Exposures in excess of the TLV trigger requirements for implementation of hearing loss prevention programs, including repeated audiometric testing, implementation of noise controls, worker training, exposure monitoring, and use of hearing protection devices (i.e., earplugs of earmuffs). The TLV makes accommodations for variable noise exposures across 5 working days, permitting exposures of up to 91 dBA $L_{EX,8h}$ on any one working day as long as the average $L_{EX,8h}$ over the 5 days is 85 dBA or less. The ACGIH TLV exposure limit, as well as the requirements triggered by exceedance of the limit, are essentially identical to the current Recommended Exposure Limit (REL) established by the National Institute for Occupational Safety and Health (NIOSH) (NIOSH 1998) as part of the agency's criteria document 98-126. The only substantive differences are in the exposure ceilings/peak limits set by the two standards (140 dBC for ACGIH, 140 dBA for NIOSH), and the lack of a mechanism to permit daily noise exposures in excess of 85 dBA $L_{EX,8h}$ provided the average across 5 working days is 85 dBA $L_{EX,8h}$ or less. The NIOSH REL is intended to reduce the excess risk of a material impairment (i.e., a Speech Intelligibility Index-weighted average hearing loss of 25 dB or greater across the audiometric frequencies of 1, 2, 3 and 4 kHz) to 8% of the exposed population over a 40-year working lifetime. NIOSH estimates a risk of material hearing impairment after a 40-year working lifetime of 1% at 80 dBA $L_{EX,8h}$, 8% at 85 dBA L $L_{EX,8h}$, and 25% at 90 dBA $L_{EX,8h}$ (NIOSH 1998).

TABLE 1. Examples of occupational and environmental noise exposure limits

	Allowable exposure (dBA) for time period					
Category/Limit	**1 week**	**8 hours**	**4 hours**	**2 hour**	**1 hour**	**Ceiling**
Occupational						
European Union Directive 2003/10/EC						
Lower Exposure Action Value		80	83	86	89	--
Upper Exposure Action Value		85	88	91	94	--
Exposure Limit		87	90	93	97	--
American Conference of Governmental Industrial Hygienists Threshold Limit Value	--	85	88	91	94	--
US National Institute for Occupational Safety and Health Recommended Exposure Limit	--	85	88	91	94	--
US Occupational Safety and Health Administration						
Permissible Exposure Limit	--	90	95	100	105	115
Action Level	--	85	90	95	100	115
Environmental						
US Environmental Protection Agency Recommended Exposure Limit	75	75	78	81	84	
World Health Organization Guideline for Community Noise						
Ambient	75	75	78	81	84	
Music						
Swedish National Board of Health and Welfare, Environmental Code						
Adults	100 for 5 hours	--	--	100	--	115
Children <13	97 for 5 hours	--	--	97	--	110

Occupational exposure limits in many countries are similar to those established by ACGIH and NIOSH (Suter 2003). For example, Germany, Sweden, Japan (Shaikh 1999), Australia (NOHSC 2000), and many other countries have adopted an 85 dBA exposure limit and use of a 3 dB exchange rate. However, unlike the ACGIH and NIOSH standards, the standards from these other countries do not provide any easily-accessible documentation of the excess risk of hearing impairment upon which the limits are based. New Zealand (Australia 2014) mentions that "AS/NZS 1269.4 predicts a 10 dB hearing loss for 95% of a noise-exposed population if they are exposed for 40 years to the noise standard of 85 dB(A) for 8 hours per day," with no specification of the audiometric frequencies at which this loss is expected to occur in the code of practice.

Occupational exposures to noise in most European countries are set according to European Union Directive 2003/10/EC (2003), which specifies three exposure limits for noise-exposed workers. These limits are set for daily (i.e., $L_{EX,8h}$) or weekly (i.e., the average $L_{EX,8h}$ across five working days in a single working week) exposures. The EU noise directive specifies a lower exposure action value of 80 dBA $L_{EX,8h}$, an upper exposure action value of 85 dBA $L_{EX,8h}$, and an exposure limit of 87 dBA $L_{EX,8h}$. Like the ACGIH and NIOSH limits, Directive 2003/10/EC specifies peak exposure limits as well as 8-hour limits; these peak limits are 135 dBC for the lower exposure action value, 137 dBC for the upper exposure action value, and 140 dBC for the exposure limit. Different requirements are triggered at each of these limits: for example, $L_{EX,8h}$ exposures in excess of 80 dBA trigger provision of hearing protection and training to exposed workers; $L_{EX,8h}$ exposures in excess of 85 dBA trigger required use of hearing protection, provision of training, and provision of audiometric surveillance for exposed workers, and; $L_{EX,8h}$ exposures in excess of 87 dBA (accounting for protection received by workers through use of hearing protection) trigger requirements for implementation of noise controls to reduce noise exposures. Note that while most EU countries have adopted Directive 2003/10/EC, not all have; for example, Sweden has set the $L_{EX,8h}$ exposure limit at 85 dBA, rather than 87 dBA (Arbetsmiljöverket 2005). Again unlike the ACGIH and NIOSH standards, Directive 2003/10/EC does not specific the excess risk of hearing impairment upon which the limits are based.

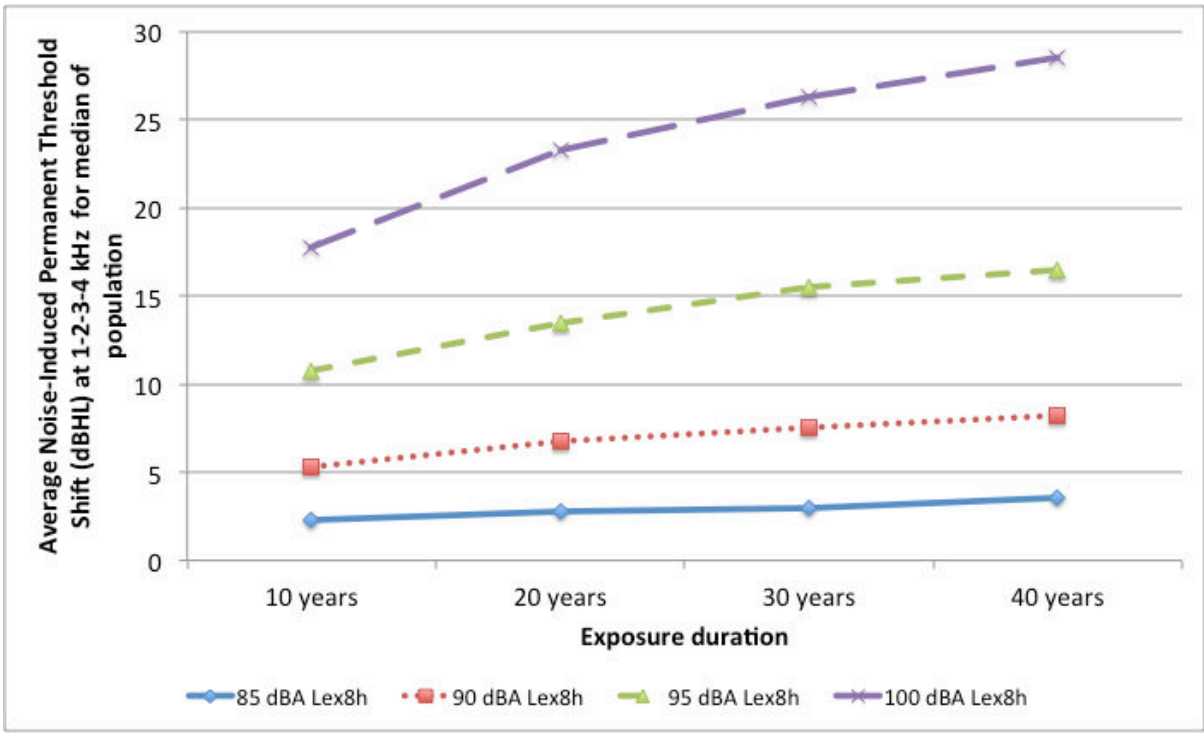
The Occupational Safety and Health Administration (OSHA) has a less protective Permissible Exposure Limit (PEL) set in regulation 29 CFR 1910.95 of 90 dBA TWA with a 5 dB exchange rate. Exposure at the OSHA PEL is expected to result in an excess risk of material hearing impairment of approximately 25% at the audiometric frequencies 1, 2, 3 and 4 kHz after a 40-year working lifetime (NIOSH 1998). That is, it is expected that approximately 25% of persons exposed at the PEL will have NIHL meeting or exceeding the definition of material hearing impairment.

A guidance document developed by the International Organization for Standardization (ISO 1999-2013 (ISO 2013)), which has also been issued with slight revisions by its member bodies (for example, American National Standards Institute S3.44-1998 (ANSI 1996). This document provides information and equations that enable the prediction of noise-induced permanent threshold shifts at various audiometric frequencies and for varying exposure durations. Note that the Introductory statement of ISO 1999-2013 (ISO 2013) explicitly states that the standard can be used to estimate the hearing impact of daily exposures to occupational and/or nonoccupational noise. The standard further states that nonoccupational noise exposure must be taken into account when considering noise-induced permanent threshold shift, except in the case where nonoccupational exposure is negligible in relation to occupational exposure. The standard also contains a passage that is extremely relevant to the current document:

> "The selection of maximum tolerable or maximum permissible noise exposures and protection requirements, as well as the selection of specific formulae for impairment risk assessment or compensation purposes, require consideration of ethical, social, economic, and political factors not amenable to international standardization. Individual countries differ in their interpretation of these factors and these factors are therefore considered outside the scope of this International Standard."

Note that exposures described in the ISO standard are described in terms of $L_{EX,8h}$, for a given number of years of exposure, and that the standard is specifically described as applying to "noise at frequencies less than approximately 10 kHz which is steady, intermittent, fluctuating, [or] irregular." Annex D of the standard includes tables with examples of noise-induced permanent threshold shift predicted at the audiometric frequencies of 0.5, 1, 2, 3, 4, and 6 kHz for L_{EX8h} exposures of 85, 90, 95, and 100 dBA for exposure durations of 10 to 40 years. Using these tables, it is possible to compute the average estimated noise-induced permanent threshold shift for the median of a population. For example, a 10 year exposure to a daily average of 85 dBA $L_{EX,8h}$ is expected to result in an average noise-induced permanent threshold shift at 1, 2, 3, and 4 kHz of 2.75 dBHL for the median individual, compared to average shifts of 5.25, 10.75, and 17.75 dBHL at 90, 95, and 100 dBA $L_{EX,8h}$, respectively. Estimated average noise induced permanent threshold shifts at 1, 2, 3, and 4 kHz, derived from Annex D (ISO 2013) are shown for different durations in **Figure 1**. ANSI standard S3.44-1998 (ANSI 1996) also includes a provision for computing average occupational noise exposures using metrics with alternative ERs (for example, the 5 dB ER used by the US Occupational Safety and Health Administration) (OSHA).

FIGURE 1. Average noise-induced permanent threshold shift (dBHL) at 1-2-3-4 kHz for median individual in population for a given exposure level and duration (derived from (ISO 2013)



Note that expected noise-induced permanent threshold shift increases most sharply in the early years of exposure, and that the rate of loss slows after that exposure window. This suggests that the first 10-20 years of exposure are the most critical in terms of risk of hearing loss, though hearing loss does continue to accrue with additional exposure time. It is important to note that these values reflect the predicted average hearing loss for the 50th percentile of a population: half the population would have more and half would have less hearing loss than illustrated in Figure 1. Care should be taken when interpreting these predictions and applying to any individual; barring prior knowledge of an individual's susceptibility to NIHL, healthcare providers are encouraged to consider each individual as carrying higher susceptibility to NIHL than the median.

1.2 Environmental noise

There are two primary environmental noise standards in use in the world today that are focused specifically on the prevention of NIHL, and at least one other minor national standard. The first is a Recommended Exposure Limit established by the US Environmental Protection Agency in 1974 (EPA 1974). This EPA limit is a 24-hour L_{EQ}, or $L_{EQ(24)}$, of 70 dBA using a 3 dB exchange rate (rounded down from 71.4 dBA to provide an additional margin of safety). For comparison to occupational exposure limits, this $L_{EQ(24)}$ value of 70 dBA is energetically equivalent to an 8-hour exposure ($L_{EX,8h}$ using the conventional occupational exposure nomenclature) of 75 dBA, assuming that the other 16 hours of exposure in a given 24-hour period have average levels of <60 dBA (EPA 1974). When the EPA recommended this exposure limit in 1974, the rationale provided was that exposures to an $L_{EQ(24)}$ of 71.4 dBA over any 24-hour period would result in a 5 dBHL or less shift in 4 kHz hearing threshold levels in 96% of the exposed population after a 40-year exposure. The EPA then added an additional margin of safety to the limit by rounding down to a recommended $L_{EQ(24)}$ of 70 dBA. In other words, this limit is intended to be completely protective against any measurable hearing loss in virtually all of the population over a 40-year exposure period. By comparison, the EPA estimated that 10 years of exposure at an $L_{EX,8h}$ of 80, 85, and 90 dBA would result in an average 4 kHz NIHL of 4, 9, and 15 dBHL, respectively. At the time the EPA recommended limit was released, the EPA made no distinction in the expected NIHL resulting from the same exposure levels of either occupational or nonoccupational noise.

In 1998, the World Health Organization adopted Community Noise Guidelines designed to protect against, among other things, NIHL (WHO 1999). The WHO adopted the same limit as the EPA – that is, an $L_{EQ(24)}$ of 70 dBA – and reported essentially the same risk of HL for this limit as did EPA in their earlier document. The WHO guidelines also note that nonoccupational exposures have been noted to result in a similar amount of NIHL as occupational exposures of a similar duration and level. The WHO guidelines differ from the EPA recommendations with regards to music exposure. The guidelines suggest that exposure through headphones should not exceed 70 dBA $L_{EQ(24)}$, or an equivalent 1 hour exposure of 85 dBA. They further indicate that maximum levels of 110 dBA L_{EQ} should be avoided to prevent "acute hearing impairment." WHO has stated that for teenagers and young children the evidence suggests that 24-hour L_{EQ} exposures <70 dBA are not expected to produce measureable NIHL. It is worth noting that the WHO also acknowledges that certain groups are especially vulnerable to small amounts of NIHL, i.e., children, those in the process of acquiring language skills, and the elderly (WHO 1999).

The Swedish National Board of Health and Welfare has recommended limits specific to music which were initially derived from their occupational noise exposure limit (Arbetsmiljöverket 2005). The limits for adults are a 1-hour L_{EQ} of 110 dBA for no more than five days per week, and a ceiling level of 115 dBA. For children, the limits are a 1-hour L_{EQ} of 97 dBA for no more than five days per week, and a ceiling level of 110 dBA (Ryberg 2009. Noise and Health). Given that these limits were derived from the upper exposure limit in use for occupational noise in Sweden, it is likely that that the limits assume some excess risk of SIHL; however, no risk estimates were identified in a search.

CONCLUSION 1: MECHANISMS FOR DETERMINING EXPOSURE LIMITS

The setting of occupational and environmental noise exposure is inherently a political issue that must consider social, cultural, and medical ramifications of exposure. The majority of nations and regulatory agencies in the world (with the notable exceptions of the US and Canada) have selected an 85 dBA $L_{EX,8h}$ as their occupational exposure limit, and in doing so have (implicitly or explicitly) accepted an excess risk of a material NIHL (i.e., 25 dBHL or greater on average across the frequencies of 1, 2, 3, and 4 kHz) of 8% after a 40 year working lifetime, or, expressed another way, an average NIHL of <10 dBHL across these frequencies in the median individual in a population after a 40 year working lifetime. Conversely, environmental noise standards (represented primarily by recommended limits from the US EPA and WHO) specify an $L_{EQ(24)}$ of 70 dBA – equivalent to an $L_{EX,8h}$ of 75 dBA with noise ≤60 dBA for the other 16 hours per day. This limit is intended to prevent any measurable hearing loss in any individual over a 40-year exposure lifetime, and includes a 5 dB margin of safety. The EU Directive for occupational noise specifies a lower exposure action value of 80 dBA $L_{EX,8h}$, which is equivalent to the EPA and WHO recommendations without the margin of safety, and is presumed to involve nearly zero risk of NIHL over a 40-year working lifetime, though this is not explicitly stated in the directive documentation.

QUESTION 2: WHAT IS THE DIFFERENCE IN NATURE OF SOUND EXPOSURE IN OCCUPATIONAL AND RECREATIONAL SETTINGS?

This question encompasses three key issues:

a. Differences in the risk of hearing loss from identical occupational and nonoccupational noise exposures
b. Differences in exposure durations for occupational and nonoccupational noise exposures
c. Differences in exposure levels for occupational and nonoccupational noise exposures

Each of these issues has substantial ramifications when considering whether there exist differences in the nature of exposure from occupational and nonoccupational sources, and the magnitude of any differences that do exist.

2.1: Differences in the risk of hearing loss from identical occupational and nonoccupational noise exposures

There is a growing body of literature suggesting a risk of temporary and permanent SIHL (Meyer-Bisch 1996; Fligor 2009; Le Prell et al. 2012; Lewis et al. 2013; Putter-Katz et al. 2015; le Clercq et al. 2016; Jiang et al. 2016; Gholamreza et al. 2016) and tinnitus (Moore et al. 2016 Nov 5; Guest et al. 2017) associated with duration and intensity of exposure to music and recreational sound and noise, though there is not complete consensus on this risk (Zhao et al. 2010; Twardella et al. 2017; Colon et al.). TTS has been demonstrated in a number of studies that had well-quantified exposure levels (Sadhra et al. 2002; Park 2003; Potier et al. 2009), and in a larger number of studies with poor exposure assessment or very crude measures of hearing (Gunderson et al. 1997). Risk of permanent hearing loss has been identified in a handful of studies, most of which suffered from inadequate or incomplete exposure assessment (Axelsson and Lindgren 1981; Mori 1985; Kahari et al. 2003; Bray et al. 2004; Jansen et al.

2009; Kim et al. 2009; Sulaiman et al. 2013; Schink et al. 2014). Not all studies of permanent hearing loss from music have identified an elevated risk from music exposure for those with typical exposures (Mostafapour et al. 1998; Weichbold et al. 2012). Given the amount of evidence available, it is reasonable to assume that sufficiently high music exposure levels can result in temporary threshold shifts, and that permanent loss is possible given sufficiently high exposure levels and long exposure durations.

There is much more limited literature comparing effects of exposures to noise and music signals that are of similar energy but differ in temporal pattern and frequency content. It is very important to note that all of the studies below focused on short-term exposures and measures of TTS; there appear to be no chronic music exposure and permanent NIHL data available to answer this question.

Lindgren and Axelsson (Lindgren and Axelsson 1983) examined 10 subjects in a study of TTS resulting from exposures to non-musical noise and found that these exposures resulted in TTS severity that exceeded those from musical noise of the same duration and overall and A-weighted sound pressure level. Four of the subjects experienced essentially the same TTS from both sources, while six experienced greater TTS from the non-musical exposure than from the musical exposure. This provides some evidence that the content of sound, and the resulting subjective perceptions of exposure may affect the risk of TTS. In a separate study, Axelsson and Lindgren (Axelsson and Lindgren 1981) documented TTS effects among musicians that were less than those of audience members.

Strasser, Erle, and Legler (Strasser et al. 2003) also studied 10 subjects over three energetically equivalent exposures to music and non-music sound over three days. Classical music (2 h exposure, mean 91 dBA) was found to be associated with substantially less TTS (10 dB vs. 25 dB) compared to industrial noise of the same duration and mean level, as well as an energetically equivalent industrial level (94 dB for 1 h) and which recovered much faster (100 min vs. 800 min). As with the Lindgren and Axelsson study, this study suggests that the content of sound may affect the risk of TTS.

Strasser, Irle, and Scholz (Strasser et al. 1999) examined four energetically similar exposures (94 dB for 1 hr): white noise, industrial noise, heavy metal music, and classical music. Industrial noise and heavy metal music were found to induce a similar amount of TTS and to require similar durations of time to recover (i.e., restitution time). However, classical music was found to result in less TTS and shorter restitution times than industrial noise, heavy metal music, or white noise. As with the previous studies, this study highlights potentially different consequences of exposure to classical music than to other types of music and industrial noise.

Mostafapour 1998 (Mostafapour et al. 1998) prospectively examined hearing loss among 50 university student subjects (mean age 22.1 years). They compared noise exposures (assessed via self-reported participation in a number of occupational and nonoccupational events, as well as firearms use) to observed degree of hearing loss. The authors noted no association between qualitative exposure to any of the assessed sources of noise and presence of a noise notch (determined via pure tone audiometry), and determined that there was low risk of NIHL among the subjects.

Finally, Swanson et al (Swanson et al. 1987) exposed 20 male subjects to music and noise of approximately equivalent energy (about 106 dBA) and for the same 10-min duration. Both exposures resulted in a significant post-exposure audiometric TTS at 4 and 6 kHz. TTS was significantly greater from music exposures among subjects who reported disliking the music used in the experiment. This study further supports the notion that subjective factors related to music may influence the risk of hearing loss resulting from music exposure, though it should be noted that audiometric testing involves a cognitive element that could conceivably be negatively influenced/biased by fatigue, loss of motivation, or frustration.

2.2: Differences in exposure durations for occupational and nonoccupational noise exposures

Lifetime exposure durations considered in current hearing loss risk models, which are uniformly based on occupational noise exposure data (ANSI 1996; ISO 2013), are far shorter than likely exposure durations for music exposures. The maximum duration of exposure for which hearing loss risk estimates are available is 40 years. This duration of exposure was appropriate in the 1960s and 1970s when early models for predicting hearing loss were created (EPA 1974), average life expectancies in high-income countries were approximately 65-70 years (National Institutes of Health 2011), and noise exposures – primarily occupational in nature – did not start until first employment in a noisy industry. Today, exposures tend to start earlier; children may be exposed from an early age to high levels of music (Jiang et al. 2016), often delivered through headphones (Basjo et al. 2016). Also, life expectancies have lengthened considerably, and now exceed 80 years in many high-income nations (National Institutes of Health 2011). These changes make the assumption of a 40-year lifetime exposure duration for music or high noise extremely conservative; in fact, lifetime exposures of 60 years (age 10 through 70) are more reasonable given current demographic and social trends. One final change that must be considered is the transition from noise being a primarily industrial exposure (with a reasonable expectation of 40 year lifetime exposure and limited contributions from nonoccupational activities) to one that, for many individuals employed in white-collar jobs, results primarily from nonoccupational activities, including listening to music (Neitzel et al. 2012). Given these substantial changes in sources and durations of exposure, the relevance of occupationally-derived hearing loss prediction models that have an upper boundary exposure duration of 40 years is highly questionable.

A secondary consideration with regards to exposure duration is the daily exposure. Whereas occupational exposures to noise have historically been restricted to 8 hours in many industries (though with exceptions; workers in some industries may work up 12-16 hours per day) (Neitzel et al. 2006). However, music exposures among both children and adults have the potential to exceed these durations daily, though it appears that most listen to music for something on the order of one to several hours per day (Zhao et al. 2010; Lee et al. 2014; Twardella et al. 2017). Neitzel et al noted that among nearly 4500 adult subjects, the vast majority of individuals were estimated to receive most of their exposure through music (Neitzel et al. 2012). Although they used MP3 players and stereos to listen to music only 2.2 hours per day on average, music was the primary source of annual noise exposure for 59% of subjects in that study. In a separate analysis of the same cohort in New York City, Lewis et al (Lewis et al. 2013) estimated that the risk of NIHL or SIHL was greater from music than from any of the other sources assessed (e.g., occupational noise, transit noise, etc.) in that study. However, the authors also noted that the greatest impairment expected among the study subjects was associated with individuals with high levels of occupational noise exposure.

2.3 Differences in exposure levels for occupational and nonoccupational sound exposures

A number of studies have evaluated maximum outputs of personal music players and demonstrated possible exposure levels that far exceed any recommended exposure limit (Fligor and Cox 2004; Torre 3rd 2008; Kumar et al. 2009). Such studies are useful to establish the potential risk of hearing loss, but do nothing to quantify that risk. Fortunately, there now exists a large and growing body of literature describing the listening levels and estimated $L_{EX,8h}$ exposures for children and young adults using portable music players. A review of this literature has already been conducted by Jiang et al (Jiang et al. 2016). This review, which involved a systematic review of the published literature and an evaluation of 26 studies that met the authors' inclusion criteria, determined that between 3 and 58% of subjects in each of the individual studies exceeded a daily dose of 85 dBA $L_{EX,8h}$ from their music listening alone. These exceedances are consistent with a number of studies that have evaluated the prevalence of overexposures to occupational noise across various industries (see, for example, Franks 1988; NIOSH 1998; Kock et al. 2004; Tak et al. 2009; Neitzel et al. 2011; Neitzel et al. 2012).

ANSI S3.44 and ISO 1999-1990(R2013) both explicitly state specific ranges of noise exposure to which their estimation equations can be applied. For both standards, this exposure range is 75 to 100 dBA (ANSI 1996; ISO 2013). ANSI states that the noise exposure for which S3.44 is relevant is:

> "…equivalent continuous A-weighted sound pressure level for a normal 8-h working day from 75 to 100 dB or an equivalent effective level), and periods of exposure lasting from 0 to 40 years. Extrapolations to higher levels are not supported by quantitative data." (ANSI 1996)

The literature describing noise doses received by children and young adults has documented a wide range of exposures. The systematic review by Jiang et al indicated that average $L_{EX,8h}$ exposures across the 26 studies reviewed ranged from 61.6 to 87.2 dBA (Jiang et al. 2016). These exposures range from values that are below the threshold for hearing loss risk consideration using the ANSI or ISO standards to values that are well within the specified range of these standards. $L_{EX,8h}$ exposures below the ranges specified in the ANSI and ISO standards are presumed to present no risk of NIHL even with chronic exposure, while the $L_{EX,8h}$ exposures within the range of the ANSI and ISO standards all have an expected risk of NIHL, with that risk depending on the magnitude of the exposure. Given the overlap between L_{EX} exposures associated with listening to music and $L_{EX,8h}$ exposures available for hearing loss prediction using the ANSI and ISO standards, it is reasonable to assume that the hearing loss predictions from these standards are appropriate for application to nonoccupational music and sound exposures.

CONCLUSION 2: DIFFERENCES BETWEEN OCCUPATIONAL NOISE AND MUSIC EXPOSURES

There are suggestions in the literature that the effects of occupational/industrial noise exposures on TTS may be worse than those of some types of energetically-equivalent music. If true, this would indicate that exposure limits based on risk of NIHL from occupational noise may be overprotective for SIHL expected to results from exposures to some types of music. There is also an indication in the literature that contemporary daily listening durations among children and young adults may be substantially greater than those traditionally associated with occupational noise exposures.

However, the tremendous variation in types and patterns of music listening warrant the adoption of conservative exposure guidelines that presume exposure to the most harmful types of music (i.e., that music exposures be considered equally as hazardous as noise exposures). The standards currently available for estimating risk of NIHL are assumed to be appropriate for daily exposures of up to 12 hours, which appears to be greater than the vast majority of listening durations reported by children and young adults (Scenihr 2008). Furthermore, the average levels of exposure associated with music are consistent with those used to predict noise in the available hearing loss estimation standards (ANSI 1996; ISO 2013). Given these findings, this report therefore recommends that exposure limits developed for occupational noise be considered appropriate for assessing risk from music and nonoccupational sound exposures, though additional exploration of the dose-response relationship between chronic music exposure and hearing loss is needed.

QUESTION 3: WHAT IS THE MOST APPROPRIATE RISK CRITERION ACCORDING TO PRESENT UNDERSTANDING AND KNOWLEDGE?

Given the information reported above, the remaining – and most important – question facing the World Health Organization Make Listening Safe working group is: how much risk is the group willing to accept in setting a recommended exposure limit? An examination of predicted noise-induced permanent threshold shift for the median population and risk for a material hearing impairment in the speech frequencies are presented in Table 2. For comparison, the predicted NIPTS at noise-sensitive frequencies are presented in Table 3 for the 10th and 5th population percentiles (those most susceptible to hearing loss from noise or nonoccupational sound).

TABLE 2. Exposure limits, predicted average speech-frequency NIPTS, and risk of material hearing impairment due to NIHL in the median population

Exposure limit (8 hour L_{EQ})	10 years of exposure		40 years of exposure	
	Risk of material impairment >25 dBHL at 1, 2, 3, 4 kHz (NIOSH)	Predicted median threshold shift at 1, 2, 3, 4 kHz (dBHL) (ISO 1999)	Risk of material impairment >25 dBHL at 1, 2, 3, 4 kHz (NIOSH)	Predicted median threshold shift at 1, 2, 3, 4 kHz (dBHL) (ISO 1999)
75	0	0	0	0
76.4	0	<5	0	<5
80	--	--	1	--
81.4	--	--	--	--
85	--	2.25	14	3.5

TABLE 3. Exposure limits, and predicted NIPTS at the most noise-susceptible frequencies (3, 4, 6 kHz) in the 10% and 5% most susceptible population

Exposure limit ($L_{EX,8h}$)	10 years of exposure		40 years of exposure	
	10th Percentile, predicted threshold shift at 3, 4, 6 kHz (dBHL) (ANSI S3.44)	5th Percentile, predicted threshold shift at 3, 4, 6 kHz (dBHL) (ANSI S3.44)	10th Percentile, predicted threshold shift at 3, 4, 6 kHz (dBHL) (ANSI S3.44)	5th Percentile, predicted threshold shift at 3, 4, 6 kHz (dBHL) (ANSI S3.44)
75	0	0	0	0
76.4	0	0	0	0.1
80	0.8	0.9	1.0	1.2
83	2.4	2.7	3.3	3.7
85	4.1	4.6	5.5	6.2

Unless an exposure level associated with zero risk of hearing loss (i.e., 75 dBA $L_{EX,8h}$, equivalent to a 70 dBA $L_{EQ(24)}$) is adopted as a recommended exposure limit, the adoption of any exposure limit is inherently a political compromise that explicitly acknowledges that some exposed individuals will suffer an adverse health outcome – in this case, permanent SIHL. Another factor that must be considered is the possibility that exposure limits intended to protect individuals against SIHL may not be protective against other, arguably more significant health effects (e.g., hypertension and myocardial infarction, which are at this point well-substantiated sequelae associated with community and occupational exposures to noise) (Passchier-Vermeer and Passchier 2000; Basner et al. 2014; Münzel et al. 2014). The consideration of these health outcomes is beyond the scope of this report, but it is important to note that there is evidence that non-auditory health impacts begin at levels substantially below those associated withSNIHL (Basner et al. 2014; Münzel et al. 2014) (e.g., <55 dBA 24-hour Day-Evening-Night noise level, L_{DEN}, equivalent to 60 dBA $L_{EX,8h}$). Additionally, the dose-response relationship between noise or sound exposure and tinnitus is not well defined. It is known that tinnitus is strongly associated with NIPTS, but an upper limit of exposure known to not cause noise-induced tinnitus has not been established (Hoffman and Reed 2004; Engdahl et al 2012). Such is a limitation of the science at present. However, there is some evidence that noise exposure can result in “hidden hearing loss” (i.e. damage to the auditory periphery, including cochlear synaptopathy, that does not manifest as elevated audiometric thresholds) (Liberman et al. 2016). While it is premature to attempt to derive a dose-response relationship for such hearing loss given the stat of the science on this issue, such loss would be expected to precede any measureable change in hearing threshold levels in the conventional range of test frequencies (i.e., 125-8000 Hz), though the relationship between noise and high frequency audiometric outcomes (e.g., 10 kHz and above) is unclear (Liberman et al. 2016).

One critical consideration in determining an acceptable exposure limit for music is the criterion specifying decibels of hearing loss that would constitute SIHL. The WHO has previously stated that hearing loss in excess of 10 dBHL average audiometric hearing threshold at 2 and 4 kHz in both ears may have an impact on speech comprehension, and that losses in excess of 30 dBHL average at 2 and 4 kHz in both ears result in a noticeable social hearing handicap (WHO 1999). However, there are other definitions of NIHL in use around the world. For example, in the United States, the American Academy of Otolaryngology – Head and Neck Surgery considers the audiometric frequencies of 0.5, 1, 2, and 3 kHz (Ward 1983). The US National Institute for Occupational Safety and Health considers 1, 2, 3 and 4 kHz in its definition of NIHL (NIOSH 1998). Other schemes for identifying and quantifying NIHL are in use around the globe. It should be noted that many of the current definitions of "hearing impairment" consider hearing loss sufficient to warrant being fitted with hearing aids as the threshold for a "material impairment." The WHO does not appear to have a specific definition of SIHL; for the purposes of establishing a recommended exposure limit, such a definition is needed unless a 70 dBA $L_{EQ(24)}$ exposure limit is adopted. In that event, sufficient literature exists to establish zero risk of NIHL at any audiometric test frequency in any individual over a 40-year exposure duration, the maximum duration that can currently be modeled (EPA 1974; WHO 1999). There are vulnerable individuals for whom this "zero risk of NIHL" is appropriate: namely, (1) young children or those not expected to have the autonomy to make informed personal health decisions; (2) persons with pre-existing hearing loss (NIHL, SIHL, or from another cause) or pre-existing tinnitus; (3) persons who have a family history of NIHL, or in whom there is reason to believe increased susceptibility to NIHL or tinnitus (e.g., persons treated with ototoxic medications; persons exposed to chemicals that might potentiate the deleterious effects of noise). For individuals not considered vulnerable (i.e., not part of one of the groups mentioned above), an exposure limit of 80 dBA $L_{EX,8h}$ (equivalent to 75 dBA $L_{EQ(24)}$) may be more appropriate, as the risk of SIHL at this exposure level is minimal (i.e., 1% risk of material impairment after 40 years of exposure). It may also be appropriate to provide a more relaxed exposure limit, respecting individuals' autonomy, while providing informed understanding of the risks. Such a more relaxed exposure limit might be 85 dBA L_{EX} (equivalent to a 80 dBA $L_{EQ(24)}$), consistent with broadly-accepted occupational exposure limits for noise.

When considering the risk of SIHL over a lifetime, it is important to note that there is already evidence of NIHL in young people first entering the workforce. Seixas et al (Seixas et al. 2004a) noted unexpectedly elevated baseline hearing threshold levels among young construction workers (mean age 27.2 +/- 7.0 years) compared to medical student controls of the same mean age. This was attributed to the construction subjects already having worked an average of 2 years in construction prior to entry into the apprenticeship program from which they were recruited into the study, but also to previous exposure to nonoccupational noise (e.g., motorcycles, music, firearms, etc.) that exceeded that of the student controls. Seixas et al followed a subset of these subjects prospectively for 10 years (Seixas et al. 2012), and found that NIHL progression exceeded that predicted by ANSI 3.44 (ANSI 1996), even when baseline hearing levels were considered.

Rabinowitz (Rabinowitz et al. 2006) examined hearing threshold levels among young adults (mean age 22.2 +/- 2.1 years) upon entry to the industrial workforce of a single multinational metals manufacturing company over a 20 year period (1985-2004). The authors did not identify an increasing trend of high frequency hearing loss over that time period, but did find that about 20% of the young workers studied in each year of the study period featured audiometric notches consistent with NIHL. As with the Seixas et al cohort (Seixas et al. 2012), some of these young workers may have had previous occupational noise exposure, and, also consistent with Seixas et al, Rabinowitz et al has observed greater rates of hearing loss among industrial workers with worse hearing at baseline (Rabinowitz et al. 2007).

Collectively, these studies suggest that a non-trivial fraction of workers entering the workforce as young adults, or early in their working career, may have already experienced SIHL. While some of this hearing loss may have resulted from previous occupational exposures in the cohort studied by Seixas et al (Seixas et al. 2004b), a substantial fraction of workers evaluated by both Seixas et al and Rabinowitz et al (Rabinowitz et al. 2006) reported noisy nonoccupational hobbies. Given that contemporary workers are likely to have exposures to occupational noise as well as nonoccupational noise (including music), and that young workers have already been noted to have hearing impairment at the beginning of their employment, the need for nonoccupational exposures limits that are truly protective (i.e., eliminate the risk of SIHL) is apparent.

There is currently no scientific evidence to suggest that a uniform standard for global application would be inappropriate. While some literature suggests that susceptibility to NIHL is influenced by factors such as skin or eye color (Henderson et al. 1993)(Mujica-Mota et al. 2015), the literature offers no definitive conclusions as to whether these factors are associated with increased risk. Given the potential vulnerability of children to noise exposures (Kujawa and Liberman 2006) – and the large uncertainty surrounding this vulnerability – it would be inappropriate and not health-protective to assume that music listeners in certain areas of the world have substantially different vulnerability to

NIHL than those elsewhere. The one exception that could be made to this statement is based on life expectancy, which can vary dramatically between different regions of the world. However, the average life expectancy is >40 years in all regions of the world, suggesting that a minimum 40-year expected exposure duration to noise is reasonable. For many regions of the world, life expectancies approach or exceed 70 years, suggesting noise exposure periods that may dramatically exceed traditional exposure duration assumptions in noise standards (OSHA 1971; NIOSH 1998; WHO 1999).

CONCLUSION 3: RECOMMENDED EXPOSURE LIMIT

In the absence of a specified WHO definition of maximum acceptable noise-induced permanent threshold shift, it is not possible to determine the risk of individuals meeting or exceeding that definition following exposure to music, and in turn impossible to determine an acceptable level of risk of SIHL. Given this situation, there are three logical alternatives. The first is adopting a recommended exposure limit that is known to eliminate the risk of NIHL in any exposed individual over the longest exposure duration that can currently be modelled. This exposure limit is a 70 dBA $L_{EQ(24)}$, equivalent to a 75 dBA $L_{EX,8h}$. Note that this limit includes a margin of safety to account for vulnerable/susceptible individuals. The second is adopting an exposure limit that will result in a very small fraction of exposed individuals encountering a material hearing impairment, but which is protective against a substantial hearing loss for virtually all exposed individuals. This exposure limit is a 75 dBA $L_{EQ(24)}$, equivalent to an 80 dBA $L_{EX,8h}$ (i.e., the current European Union occupational noise lower exposure action value). It is worth noting that this 80 dBA $L_{EX,8h}$ exposure limit is intended to nearly eliminate the risk of measurable NIHL following a 40-year working lifetime. Conversely, however, the standard may not be sufficiently protective. Lifetime exposures to music and noise may reasonably be expected to exceed a cumulative duration greater than 40 years, the loss from which cannot be accurately estimated using existing predictive standards (EPA 1974; WHO 1999), though it is worth noting that these models predict that the greatest rate of change in hearing from sound exposure will occur in the first ten years of exposure, and that exposures beyond that time contribute much less to overall SIHL. Nevertheless, despite these uncertainties, adoption of an 80 dBA $L_{EX,8h}$ limit for exposure to music likely represents an optimal trade-off between being sufficiently protective and being onerous and/or technically or socially infeasible. Should the EU occupational noise lower exposure action level (80 dBA 8-hour $L_{EX,8h}$) be deemed too restrictive or otherwise not respectful of the autonomy of individuals, a less restricted exposure limit should be considered. This third, "liberal" recommended exposure limit, applicable to individuals willing to tolerate modest risk for a small degree of NIPTS, but still sufficiently protective of the vast majority of people exposed to nonoccupational music exposures, is 85 dBA 8-hour $L_{EX,8h}$ (i.e., 80 dBA $L_{EQ(24)}$; 94 dBA 1-hour L_{EQ}). This recommended limit coincides with occupational exposure limits in use in most countries worldwide, and would be appropriate for individuals willing to accept a higher risk of SIHL.

Limitations to Conclusion 3 include:

(1) **There is no recommended exposure limit based on dose-response relationship between sound exposure and tinnitus; thus, these recommendations may, or may not, be appropriate for mitigating risk for sound-induced tinnitus. However, based on limited evidence (Moore et al. 2016 Nov 5; Guest et al. 2017), it appears that sound-induced tinnitus**

may precede measurable SIHL, suggesting that more stringent exposure limits may be necessary to protect against noise-induced tinnitus.

(2) **These recommendations do not specifically consider the impact of additional decrease of hearing sensitivity in those individuals who have pre-existing hearing loss (from sound, noise, or from other causes).**

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