Occupational noise exposure standards and noise exposure guidance for the public need to be reduced to prevent noise-induced hearing loss

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ABSTRACT

Significant hearing loss is not part of normal physiological aging, but largely represents noise-induced hearing loss (NIHL) from cumulative lifetime noise exposure. The only evidence-based noise exposure level to prevent NIHL is the US Environmental Protection Agency's calculated 70 A-weighted decibel (dBA) time-weighted average for 24 hours ($L_{eq(24)}$=70). For several reasons, both occupational noise exposure standards and noise exposure guidance for the public need to be reduced to prevent NIHL. Occupational noise exposure standards, such as the US National Institute for Occupational Safety and Health 85 dBA recommended exposure limit, assume workers have quiet when not at work. Multiple studies in several countries document that this is no longer true. Therefore, according to the equal energy hypothesis, occupational noise exposure must be reduced to prevent workplace hearing loss. Additional reasons mandating reduction of occupational noise exposure standards include 1) the need to consider lifetime noise exposure, not just 40-year occupational exposure, and 2) the fact that occupational standards are based on older research using limited frequency audiometry to detect hearing loss. More sensitive tests of auditory damage, such as extended range audiometry, speech-in-noise testing, and questions about tinnitus, hyperacusis, and difficulty in localizing noise sources, would show a greater prevalence of noise-induced auditory damage much earlier. For the same reasons, guidance and recommendations about noise exposure for the public must also be reduced. The actual safe noise level to prevent NIHL may be as low as 55 dBA, the effective quiet level required to recover from noise-induced temporary threshold shift.

Keywords: Occupational noise exposure, public noise exposure, noise-induced hearing loss, occupational standards, public health

Introduction

Hearing loss is prevalent in older people and increases with advancing age[1], but significant hearing loss is not part of normal physiological aging and largely represents noise-induced hearing loss (NIHL) from cumulative noise exposure.[2,3] A number of studies done in isolated populations not exposed to loud noise, most done in Africa in the 1960s, showed that without noise exposure hearing was preserved into old age.[2,4] That hearing loss in the elderly is largely due to noise-induced damage to cochlear hair cells was recently confirmed by pathological studies of donated temporal bones.[3] The only widely available treatment for NIHL is amplification, with cochlear implants reserved for the profoundly hearing impaired. Unfortunately, neither treatment restores normal hearing.

It is important to differentiate between normal physiological aging and abnormal pathological aging. Thinning, graying hair and decreased athletic performance are among the many sequelae of normal aging. Obesity, hypertension, diabetes, muscle weakness, skin cancers, and hearing loss are not. Why does this matter? If changes with age are inevitable, like thinning

graying hair, only cosmetic measures can be employed to deal with them. But if changes can be prevented by altering one's behavior, perhaps some of the changes commonly associated with aging can be prevented or delayed.

There are four broad causes of abnormal or pathological aging: 1) disuse atrophy, 2) bad diet, both in terms of quantity and quality, 3) obesity, resulting from a combination of bad diet and lack of sufficient exercise, and 4) exposures. Appropriate behavioral changes address all four. Regular exercise can help maintain muscle tone and intellectual activity might prevent cognitive impairment. The Mediterranean diet has been shown to prolong healthy life. Both diet and exercise help maintain ideal body weight, which is associated with reduced morbidity and mortality. Avoidance of sun exposure prevents deep wrinkles and pigmentation changes.[5] Avoidance of noise exposure prevents NIHL.

Prevention is the key. Prevention of disease, including prevention of NIHL, is far better and almost always less expensive than treatment or rehabilitation.[6] This is certainly true for NIHL, which is the only form of hearing loss that is entirely preventable. To prevent NIHL, it is important that hearing health professionals, acoustic engineers, and the public know what the safe noise exposure level is. Promulgation of inaccurate information about safe noise exposure levels endangers both workers' and the public's auditory health, misleadingly informing them that potentially harmful noise exposure levels are safe. Recommendations and requirements for occupational noise exposure assumed workers had quiet when not at work, something no longer true. Therefore these recommendations and requirements must be adjusted downwards to prevent occupational NIHL. Since noise exposure guidance for the public is based on occupational noise exposure studies, and sometimes on existing occupational noise recommendations, this must also be revised downwards. Occupational noise exposure levels are not safe for the public, especially not for children and other sensitive populations.[7,8,9] National and international health authorities, including the National Institute for Occupational Safety and Health (NIOSH) and Centers for Disease Control and Prevention (CDC) in the United States (US), health ministries in European Union and other countries, and the World Health Organization (WHO), must specify safe noise exposure levels for workers and provide correct information about safe noise exposure levels to the public to prevent NIHL in both groups.

A new definition of noise: Noise is unwanted and/or harmful sound

The standard definition of noise, "Noise is unwanted sound," is obsolete, ignoring the fact that wanted sound can be harmful. Wanted sound can cause hearing loss, tinnitus, and hyperacusis, as can unwanted sound, and both can have non-auditory health effects.[10] Noise damages cochlear hair cells, with NIHL caused by cumulative occupational and non-occupational noise exposure.[11] A better definition is, "Noise is unwanted and/or harmful sound." [12]

This paper will focus on the US NIOSH recommended exposure limit (REL) for noise but other countries' occupational noise exposure standards also need to be revised downwards. Noise is different from most industrial exposures, e.g., toxic solvents or ionizing radiation, because exposure occurs outside the workplace. Noise exposure begins in utero and continues outside the work environment during working years and into retirement years. According to the equal energy hypothesis, equal amounts of sound energy will produce equal amounts of hearing impairment, regardless of how the sound energy is distributed in time.[13] To protect workers from occupational NIHL, the REL for noise must be reduced to reflect lifetime non-occupational noise exposure. Although the NIOSH REL includes exposure from both impulsive and continuous noise, it may not adequately account for the adverse effects of impulsive noise. Non-Gaussian

noise exposure may have a disproportionate impact on hearing[14], and in animal models brief high-intensity noise exposures damage cochlear synapses even if hair cells remain undamaged.[15]

Noise exposure causes hearing loss in the public, not just in workers with occupational exposure.[16,17.] This fact was not recognized until I pointed this out to CDC in 2015.[18] The only evidence-based safe noise exposure level to prevent NIHL is 70 dBA ($L_{eq(24)}$= 70) time-weighted average for a day. This was calculated in 1974 by the US Environmental Protection Agency (EPA), with "the 24-hour exposure level…derived from data on 8-hour daily exposures over a 40-year working life," not considering lifetime exposure.[19] Downward revision of occupational noise exposure recommendations and requirements with subsequent downward revision of noise guidance for the public will not only protect workers but may help prevent NIHL in more than one billion young people around the world.[20]

Humans and our mammalian and primate ancestors evolved in quiet, with few things in nature- perhaps thunderstorms, waterfalls, earthquakes, the crash of waves for those living near the ocean, or occasional calls of animals or of birds gathered at dusk- exposing them to loud noise. The National Park Service noise maps (see Figure 1) show that without anthropogenic noise, ambient noise levels in the United States range from approximately 20-40 dBA at the 50th percentile.[21] Similar noise maps are not available for other countries but would likely yield similar results.

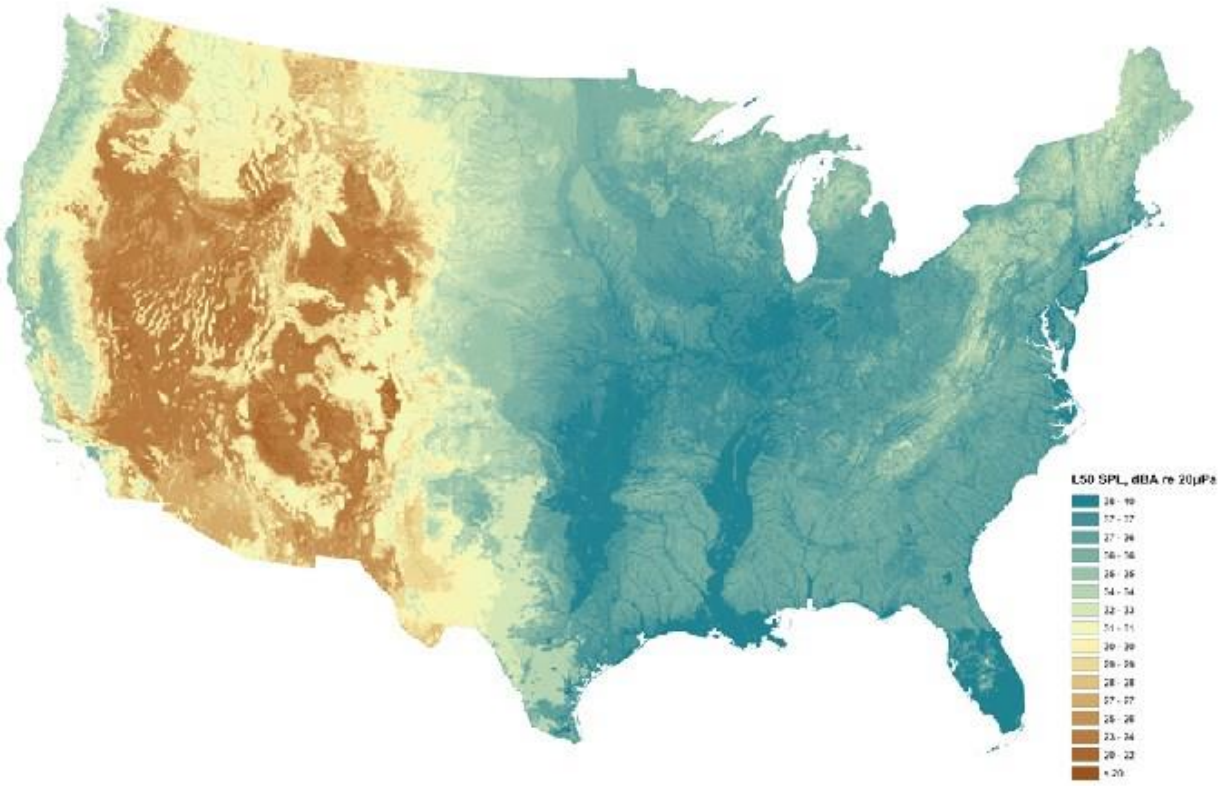
Because of the importance of sensitive hearing for survival- for avoiding predators, finding food, and communication, among other activities- animals, including humans, evolved almost no protective mechanisms against loud noise. Unfortunately, loud noise damages hearing. The mechanisms by which NIHL occurs are now well-understood, down to the cellular, molecular, and genetic levels.[11,22] Understanding these processes has led to consideration of targets for pharmaceutical intervention to prevent NIHL.[23]

Occupational hearing loss

Occupational hearing loss was recognized by the Middle Ages, in blacksmiths, stonemasons, and miners. As Murphy[24] notes, in 1713 Ramazzini described occupational hearing loss among copper workers in Venice. During the industrial revolution, occupational hearing loss was recognized in factory workers and boilermakers, with hearing loss in those making steam boilers becoming known as boilermakers' disease. After the advent of gunpowder, hearing loss was recognized as a hazard for the military.[25] The adverse effects of occupational noise exposure[26] and the history of occupational noise regulations in the United States have been reviewed.[27]

Until relatively recently, non-occupational noise exposure was rare, perhaps limited to hunters, woodworkers, and musicians. This began to change in the 1950s and 1960s, with the development and diffusion of new technologies and a growing middle class able to purchase electric appliances, electric and gasoline power tools, and home stereo systems. The dangers for hearing posed by non-occupational noise exposure were recognized in 1966.[28] In the 1970s and 1980s, advances in electronics led to increased non-occupational noise exposure due to cheaper, better amplifiers allowing less distorted amplified sound levels at home and at cultural and sports events, with pervasive background music in elevators, retail stores, and restaurants, and more recently widespread use of personal audio systems. Today the major sources of non-occupational noise exposure are personal audio systems, leisure noise[29], household appliances, and power tools and landscape maintenance equipment.[30]

Figure 1. US National Park Service noise map, without anthropogenic sound.



Reproduced from National Park Service. Mapping Sound.[21]

Non-occupational noise exposure

Non-occupational noise exposure was not relevant when the noise exposure-hearing loss studies upon which the NIOSH REL and the EPA safe noise level were done. As Neitzel and Fligor noted, “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, as average life expectancies in high-income countries were approximately 65–70 and noise exposures—primarily occupational in nature—did not start until first employment in a noisy industry.”[31] They describe the differences between occupational and non-occupational noise exposure, but it is now well-established that non-occupational noise exposure causes hearing loss in the public.[16]

Tables 1-1 and 1-2 of the NIOSH 1998 noise criteria monograph demonstrate the mathematical relationships between exposure duration, noise level, and noise dose, based on the NIOSH REL.[13] In a NIOSH Science Blog, Kardous et al. stated: “In 1998, NIOSH established the REL for occupational noise exposures to be 85 decibels, A-weighted (dB[A]) as an 8 hour time-weighted average. Exposures at or above this level are considered hazardous. **The REL is based on exposures at work 5 days a week and assumes that the worker spends the other 16 hours in the day, as well as weekends, in quieter conditions**.”[8] [Bolding added]

Many studies, using different methods in different populations in different countries, show that daily noise exposures often exceed an $L_{eq(24)}$ of 70 dBA even without occupational exposure. Flamme et al.[32] measured noise exposures in Kalamazoo, MI, using dosimetry. Median average daily noise exposures were 79 dBA for men and 77 dBA for women. Neitzel et al. estimated average annual noise exposures in New York City to be 76.8 dBA for transit users and 76 dBA for non-users.[33] In Sweden, Neitzel et al. measured total noise exposure for office workers, day care workers, and military flight technicians to average 78.6 dBA with 57.5% of total noise exposure outside work hours.[34] In Washington state, again using dosimetry, average non-occupational noise exposures were 74 dBA.[35] For the studies in which the percentage of subjects exceeding the EPA 70 dBA noise exposure level to prevent NIHL was reported, exceedance ranged from 70% to 91%.

Additional reasons the NIOSH REL must be revised downwards

The NIOSH REL must be revised downwards for at least three additional reasons. First, as already discussed, lifetime noise exposure must now be considered. Noise exposure often starts in early childhood, with toddlers starting to listen to video soundtracks using headphones as early as age 3, children attending noisy parties and watching movies with soundtracks in the 100-125 dBA range, with more exposure in adolescence through use of personal listening devices.[36] Before the COVID-19 pandemic, life expectancy in most industrialized nations was approaching or even exceeding 80 years. The additional years of noise exposure before starting work and after retirement, in the United States now occurring on average at age 64, must be considered in recommending occupational noise exposure levels to prevent workplace auditory damage while working and to preserve hearing for retirement years.

The second additional reason the NIOSH REL must be recalculated downwards is that NIOSH used the damage risk criterion of inability to understand speech, as measured by limited range pure-tone audiometry at 1, 2, 3, 4 kHz, to determine the adverse effects of occupational noise exposure.[13] Limited range pure-tone audiometry is an insensitive measure of noise-induced auditory damage. Liberman et al. showed that more sensitive measures of auditory damage, including questions about tinnitus, noise sensitivity, and speech in noise difficulty, extended frequency audiometry to 20 kHz, formal speech in noise testing, and research techniques including diffusion product otoacoustic emissions testing and electrocochleography, find evidence of auditory damage in noise-exposed subjects despite normal audiometry from 0.25-8 kHz bilaterally.[37] It is highly likely that testing workers with more sensitive tests will find an increased prevalence of auditory damage at much lower exposure levels after much shorter exposure times.

The third additional reason the NIOSH REL must be recalculated downwards is that it uses 25 dB hearing threshold loss as the measure of auditory damage. A 25 dB hearing threshold level decrement is not normal. It denotes sufficient hearing loss to cause speech-in-noise difficulties. As Pienkowski has noted, normal hearing is actually a zero threshold hearing loss.[38]

Occupational noise exposure standards worldwide

The historical development of occupational standards in other countries is beyond the scope of this paper, but most appear either to be based on the NIOSH REL or on studies similar to those on which the NIOSH REL is based. As reported by Roberts and Neitzel, with definitions varying from country to country, actionable, allowable, or permissible occupational noise exposure limits ($L_{ex(8)}$) range from 80 dBA to 90 dBA.[39] Therefore, the need for a downward recalculation likely

extends to occupational noise exposure recommendations or standards in many if not most countries worldwide.

Recommendations, advice, or guidance for public noise exposure

The real importance of lower occupational noise exposure levels is not just for prevention of occupational NIHL, but for prevention of NIHL in the general public. It appears to be human nature to want "more", whether possessions, wealth, food, alcohol, speed, or noise. Members of the public are not exposed to continuous sound above 85 dBA for 8 hours for 240 days annually, and are unlikely to have 40 years of such exposure. If, however, 85 dBA is considered a safe noise exposure level or the sound pressure level at which auditory damage occurs, greater noise exposure is likely. Excessive non-occupational noise exposure must be causing the 24% prevalence of NIHL in American adults age 20-69, the majority without significant occupational noise exposure.[16] A similar prevalence of hearing loss have been reported in European countries.[40] Non-occupational noise exposures routinely approach or exceed 100 dBA and may reach 125 dBA, often in short bursts of noise, e.g., from exposures in clubs or at concerts, or from movie soundtracks, appliances, or power tools.[30] Damage from these brief intermittent high-intensity noise exposures likely causes most non-occupational NIHL.

Even when the NIOSH REL or similar occupational noise exposure levels are not directly cited as a safe noise exposure level for the public, 85 dB or dBA crops up with disturbing frequency in safe listening guidance for the public. For example, 85 dB is used as the standard for headphones marketed as safe for children as young as 3 without any exposure time limit specified.[41] Some organizations, e.g., the American Speech-Language-Hearing Association, appear to cite the NIOSH REL directly, stating, "Sounds at 85 dBA can lead to hearing loss if you listen to them for more than 8 hours at a time… The safe listening time is cut in half for every 3-dB rise in noise levels over 85 dBA."[42] In 2015, WHO extrapolated the occupational standards to the recreational setting.[43] As noted previously, the NIOSH REL is not a safe noise exposure level for the public.[7,8] In 1999, WHO recommended only one hour at 85 dBA to prevent NIHL in the public.[44]

The EPA's calculated noise level to prevent hearing loss is not a recommendation, and in the United States there are no federal guidelines, recommendations, or standards for non-occupational noise exposure.[16] Some noise exposure levels calculated, recommended, or advised for the public worldwide are listed in Table 1.

What is the actual safe noise exposure level to prevent noise-induced hearing loss?

What is the actual safe noise exposure level to prevent NIHL? This noise exposure level is not known and may never be known because it is now unethical and illegal in most countries to injure research subjects. Furthermore, 80-year lifetime studies correlating actual measured or even estimated noise exposures and hearing loss are unlikely ever to be done. The safe noise level certainly isn't any of the occupational noise exposure recommendations or standards, none of which prevents hearing loss. For the public, risks of exposures must be very low, with acceptable risks from exposures for the public range from 1 in 10^4 to 1 in 10^6.[45] For the reasons discussed above, it can no longer be the EPA safe noise exposure of a time-weighted average of 70 dB for 24 hours, because EPA did not consider lifetime noise exposure and the studies on which EPA based its calculations used limited frequency pure-tone audiometry.

Some clues to what the safe noise exposure level come from older research published decades ago. Before current research subject protections were established, noise-induced temporary

threshold shift (NITTS), the temporary muffling of sound after loud noise exposure, was used as a measure of auditory damage from noise.[46] NITTS is real and measurable phenomenon, even though any auditory symptoms likely indicate that permanent auditory damage has occurred.[38,47] The effective quiet level is the sound pressure level needed for recovery from NITTS. Studies done in the 1970s suggest that the effective quiet level is about 55 dBA, with one study finding it to be 48 dBA.[32] The safe noise exposure level to prevent NIHL may be a lifetime exposure level near 55 dBA.

Table 1. Recommendations, guidance, or advice for public noise exposure

Organization	Description	Noise Level	Reference (Year)
EPA	24 hour time-weighted average	70 dBA	Environmental Protection Agency[19] (1974)
WHO	1 hour noise dose	85 dBA	Berglund et al.,[44] (1999)
WHO	Recreational noise, yearly average	70 dB	World Health Organization[48] (2018)
ITU	Personal listening devices 40 hrs/wk	80 dBA/75 dBA for sensitive listeners	International Telecommunications Union[9] (2022)
CDC	Noise that may start to damage hearing	70 dB	Centers for Disease Control and Prevention[49] (2022)
NIDCD	Which sounds can cause hearing loss	Those at or above 85 dBA	National Institute on Deafness and Other Communication Disorders[50] (2022)
UK Royal National Institute for Deaf People	Threshold level at which hearing can become damaged over time	85 dB	RNID[51] (2023)
Dangerous Decibels	Safe for 8 hours	85 dBA	Dangerous Decibels[52] (2023)

Table 1 is reproduced in accordance with publication policies of the Acoustical Society of America from Fink, D. The recommended exposure limit for occupational noise needs to be revised downwards. Proc. Mtgs. Acoust. (2023) 50,040002. https://doi.org/10/1121/2.0001729

This analysis is not new. In 1994 Kryter wrote, “Several investigators, using human and animal subjects, have found that recovery from Temporary Threshold Shift is reduced when the level of background noise in periods between exposures to more intense noise was no higher than L_A 50-70 dB. Not until the “noise” in the recovery periods was less than those levels did full recovery continue. This maximum level, perhaps for humans around L_A55 for an octave band and L_A60 for broadband noise, is called *effective quiet*, and presumably indicates a level, perhaps a 24-h ,$EL_{Aeq,24h}$, energy level, required for complete avoidance by the average, and 50%ile, ear of sound induced permanent threshold shifts during a lifetime.”[53] Pienkowski also noted that for children, auditory damage may begin at noise levels of 50-70 dBA.[39]

Hearing involves stimulation of cochlear hair cells by sound pressure waves followed by mechanotransduction, i.e., the transformation of the physical distortion of the hair cells into electrical impulses, which are then transmitted to the brain, where they are processed to allow perception of sound. Mechanotransduction involves production of reactive oxygen and nitrogen compounds, which in turn are reduced by compounds such as reduced nicotinamide adenine dinucleotide phosphate, abbreviated NADPH. The effective quiet level likely represents the sound pressure level at which these reversible chemical processes are overwhelmed, cumulatively causing noise-induced hearing loss over time. Of note, 55 dBA is the approximate sound pressure level of human speech in a quiet environment. It appears that humans evolved to be able to communicate with each other without damaging our hearing, but any sounds greater than that relatively low sound pressure level have the potential for auditory damage.

A useful albeit imperfect analogy may be the effect of ultraviolet light on the skin. Ptosis (sagging of the skin) is part of normal physiological aging, due to the effect of gravity on collagen fibers in the skin. Deep wrinkles and pigmentation changes are not.[5] Without sun exposure, skin remains smooth without pigment changes throughout life. Similarly, without exposure to loud noise, there will be little to no decrement in auditory sensitivity over time. Rosen et al. found the decrease in hearing threshold to be 9 dB in old age, which does not meet the WHO definition of hearing loss.[4] That amount of hearing loss may be true age-related hearing loss, not the bilateral 25 dB decrement reported by Lin.[1]

Conclusion

The basic principles of how NIHL occurs, based on current understanding of the mechanisms of NIHL, and the literature reviewed, amply make the case that the NIOSH REL must be revised downwards to prevent occupational NIHL. The NIOSH REL calculations assumed workers had quiet when not at work, something no longer true. Inclusion of noise exposure in childhood and adolescence before starting work, during work years, and in retirement also means that occupational noise exposures must be reduced to prevent workplace NIHL. And to prevent hearing loss in old age, occupational and non-occupational noise exposure must be reduced even further.[3,7,,30]

That is the real reason occupational noise exposure guidelines or requirements must be revised downward, not just to protect workers from occupational NIHL, but more importantly to prevent NIHL in the public. Prevention of disease is almost always better and less costly than treatment.[6] The only current treatment for hearing loss is amplification, which is costly and does not restore normal hearing. Aside from the stigma of hearing loss[54], which discourages people from using hearing aids, no country can afford to provide these to all its citizens with NIHL.[55] As Bisgaard et al. state, “The world-wide hearing aid coverage is 10-11% depending on the prevalence of data source. For all low- to middle-income regions that make up 85% of the world population, the coverage ranges from 1.5% to 12%. In the group of high-income countries as defined by WHO, the coverage is 57%.”[56] Prevention of NIHL is much cheaper than prescription or over-the-counter hearing aids, and should be affordable in almost all countries.

Hearing loss with age is commonly called *presbycusis* or *age-related hearing loss*, but a more accurate term may be Kryter’s term *sociocusis* or my suggested term, *noise-induced hearing loss in the elderly*. Lower recommendations or standards for occupational noise exposure may lead to guidance or recommendations for lower public noise exposure. That in turn may encourage regulators to require lower noise levels in public places, e.g., restaurants, bars, retail stores, transportation hubs, in public transit, and other places. Even if the information about safe

noise exposure levels is not used as the basis for legislation or regulation, but is merely provided to the public as information or guidance or ideally recommendations, at least some members of the public may be motivated to reduce their and their children's noise exposure.

A quieter world will be a better and healthier place for all.

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