Chapter 2
The Public Health Significance of Noise-Induced Hearing Loss

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1 Introduction

Recognition of hearing loss resulting from noise exposure dates back at least as far as Ramazzini's (1713) classic occupational medicine treatise *De Morbis Artificum* (Diseases of Workers). Ramazzini's vivid discussion of noise-induced hearing loss (NIHL) is notable for its recognition that exposure to both occupational and environmental noise can lead to hearing loss in individuals and entire populations. In describing the coppersmiths of Venice, he compared them to an environmentally exposed population in Egypt:

> …at Venice, these workers are all congregated in one quarter and are engaged all day in hammering copper to make it ductile so that with it they may manufacture vessels of various kinds. From this quarter there rises such a terrible din that only these workers have shops and homes there; all others flee from that highly disagreeable locality. One may observe these men as they sit on the ground, usually on small mats, bent double while all day long they beat the newly mined copper, first with wooden then with iron hammers till it is as ductile as required. To begin with, the ears are injured by that perpetual din, and in fact the whole head, inevitably, so that workers of this class become hard of hearing and, if they grow old at this work, completely deaf. For that incessant noise beating on the eardrum makes it lose its natural tonus; the air within the ear reverberates against its sides, and this weakens and impairs all the apparatus of hearing. In fact the same thing happens to them as to those who dwell near the Nile in Egypt, for they are all deaf from the excessive uproar of the falling water.

Given the inclusion of NIHL in the first major textbook on occupational diseases, it is surprising that, 300 years later, there is still significant controversy about the true prevalence and public health importance of this condition. This chapter reviews

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C.G. Le Prell et al. (eds.), *Noise-Induced Hearing Loss: Scientific Advances*, Springer Handbook of Auditory Research 40, DOI 10.1007/978-1-4419-9523-0_2,

Table 2.1 Relationship between prevalence, severity, and public health impact of a medical condition

		Severity	
		Low	High
Prevalence	Low	Low public health impact	Potential public health impact
	High	Potential public health impact	High public health impact

the evidence for the public health impact of NIHL and provides a framework for viewing NIHL as a public health issue.

Assessing the public health impact of NIHL involves consideration of both its prevalence in a particular population, as well as the severity of impact of the condition on affected individuals and populations as a whole. As Table 2.1 shows, diseases that are highly prevalent and severe, such as cardiovascular disease and cancer, obviously have a high public health impact, whereas rare or mild diseases do not. Yet even if medical conditions are relatively mild in terms of individual morbidity, they can have a significant public health impact if they are highly prevalent. Therefore, an analysis of the public health importance of NIHL needs to assess carefully the evidence regarding the prevalence and severity of the condition.

2 Estimates of the Public Health Impact of NIHL

Over the years, estimates of the prevalence and severity of NIHL have varied widely. Key reasons behind this variability seem to include the lack of a common case definition for NIHL, the difficulty of distinguishing NIHL from age-related hearing loss (presbycusis), uncertainty about the size of the population that is exposed to harmful levels of noise, and the many ways to assess the impact of the condition on individuals. As this chapter discusses, recent research findings suggest both that older adults are retaining good hearing longer in life (suggesting that previous assumptions about the contribution of aging to adult hearing loss may be flawed) and that NIHL may be increasing as a problem in children and adolescents. Both of these findings, if confirmed, could enhance our appreciation of the relative contribution of NIHL to the overall burden of hearing loss in the population.

2.1 Lack of a Common Case Definition for NIHL

As an example of the diverse ways that NIHL is defined and tracked, current regulatory practice in the United States regarding NIHL employs several different definitions of hearing loss. These definitions include a certain degree of audiometric

Table 2.2 Hearing loss metrics in use in the United States

Hearing loss metric	Criteria
Occupational Safety and Health Administration (OSHA) Standard Threshold Shift (STS)	10-dB change from the baseline audiogram in the average of hearing threshold levels at 2, 3, and 4 kHz, with age correction allowed
OSHA "recordable" hearing loss	10-dB shift from baseline as described above with the average of absolute hearing threshold levels at 2, 3, and 4 kHz greater than or equal to 25 dB HL
American Medical Association (AMA) Hearing Impairment	Hearing threshold average at 0.5 (500 Hz), 1, 2, and 3 kHz greater than 25 dB HL, with 1.5% monaural impairment for each decibel greater than 25 dB

"shift" from a baseline audiogram for a noise-exposed worker being tested in a hearing conservation program [U.S. Occupational Safety and Health Administration (OSHA) STS (OSHA 1983) and OSHA recordable hearing loss], as well as absolute value cutoffs for hearing impairment (AMA hearing impairment: American Medical Association 2008). These definitions are shown in Table 2.2.

Many other governmental definitions of hearing loss are in use in different countries, there are no agreed upon international standards for tracking NIHL, and even across different states in the United States there are varying definitions of compensable hearing loss (Dobie and Megerson 2000). The research literature is similarly diverse, with some studies using governmental definitions to define outcomes and others using hearing threshold levels at single noise-sensitive frequencies, or other combinations of frequencies.

Another method of defining NIHL has been through the use of "notch definitions" determining the presence or absence of a high-frequency "notching" of the audiogram. Such a notch is typically centered around 3,000 or 4,000 Hz with recovery at 8 kHz, (ACOEM Noise and Hearing Conservation Committee 2003), as shown in Fig. 2.1.

The definition of a noise notch provided by Niskar et al. (2001) requires all of the following criteria to be met: (1) thresholds <15 dB HL at 0.5 and 1.0 kHz; (2) 3, 4, or 6 kHz threshold at least 15 dB worse than thresholds at 0.5 and 1 kHz; and (3) 3, 4, or 6 kHz threshold at least 10 dB worse than 8-kHz threshold. Coles et al. (2000) offered an alternative medicolegal definition of a noise-notch, including a hearing threshold at 3, 4, or 6 kHz that is at least 10 dB greater than at 1 or 2 kHz, and at least 10 dB greater than at 8 kHz. To date, however, there remains no commonly agreed upon definition for an audiometric notch (McBride and Williams 2001), although some published criteria demonstrate good agreement with expert judgment (Rabinowitz et al. 2006a). It is clear that the diagnosis of NIHL, and the estimates regarding the prevalence of NIHL, will vary as a function of the definition selected; thus, comparisons across studies must carefully compare the specific criteria used in each one.

In addition to audiometric definitions, other studies of NIHL prevalence may rely on individual self-report of hearing difficulty in surveys, or use other testing modalities

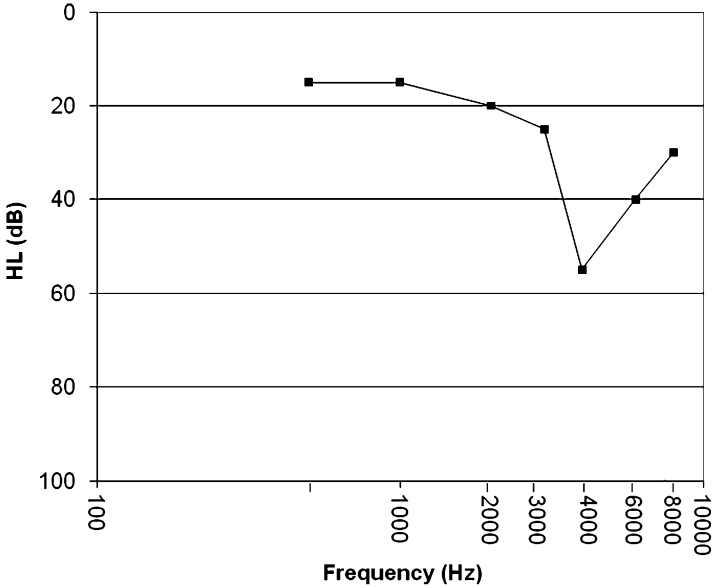

Fig. 2.1 Audiogram showing typical high-frequency "notching" of NIHL

such as otoacoustic emissions that may be sensitive indicators of noise-induced cochlear damage (Korres et al. 2009). As a result of the heterogeneity of these case definitions, comparisons between published studies of NIHL prevalence are often difficult.

2.2 *Differentiation Between NIHL and Presbycusis*

One of the dilemmas in assessing the importance of NIHL as a public health problem is the clinical similarity between presbycusis and NIHL. A central feature of both conditions is sensorineural hearing loss involving predominantly the higher audiometric frequencies. The presence of an audiometric "notch," as described earlier, is thought to be suggestive of noise-induced damage rather than presbycusis (ACOEM Noise and Hearing Conservation Committee 2003). However, as Taylor demonstrated in his studies of noise-exposed weavers (Taylor et al. 1965), over time the effects of noise and aging may superimpose and make a noise notch less evident, thus making it harder to distinguish the relative contributions of noise and aging (for review of age/noise interactions, see Bielefeld, Chap. 10).

Some recommend the use of age-standardized tables of the amount of hearing loss that would be expected in the absence of noise exposure in order to adjust, or "age-correct," for the effects of age and separate out the effects of noise. Examples of such tables include the annexes of the American National Standards Institute (ANSI) standard 3.44 (ANSI 1966). The OSHA noise standard uses similar methods to create an age correction table that can be applied to individual audiograms. Such a process of age standardization can have validity when applied to a population, but will inevitably misclassify some individuals by either under- or overestimating the relative effects of aging and noise for that individual. As a result, some agencies discourage the use of age correction for individual audiograms (NIOSH 1998).

Of course, the use of such aging tables to determine the amount of NIHL occurring in either an individual or a population is based on the dual assumptions that a population can be found without significant noise exposure in order to display the effects of aging alone, and second that the pattern of hearing loss in the reference population can be applied to other populations. In terms of the first issue, although it is possible to find populations who deny working at jobs with significant noise exposure, the ubiquitous environmental noise exposures of daily life as well as non-occupational noise exposures such as power tools and motorized vehicles may be present in the "nonindustrial noise-exposed population" (NINEP) used to develop some of the age tables. In the context of this discussion, it is worth considering the published cross-sectional surveys of the hearing status of populations living in the absence of significant occupational or nonoccupational noise exposures, such as the Mabaan tribe of Sudan; those studies report only minimal changes in hearing with advancing age (Bergman 1966). Therefore, by assuming that a certain proportion of an individual's hearing loss is due to "aging," it is possible that one is underestimating the chronic effects of nonoccupational noise exposure (socioacusis) on his or her hearing status.

In terms of whether the background rate of age-related loss in the population is accurately reflected by standard aging tables such as those in ANSI 3.44, there is evidence suggesting that the general U.S. population may now be exhibiting less "age-related loss" than did previous generations. A recent study explored the effect of age cohort on hearing loss risk among 5,725 adults living in Beaver Dam, Wisconsin, by looking at the rates of hearing impairment in each 5-year birth cohort (Zhan et al. 2010). This study found that after controlling for age, every 5-year increase in birth year lowered the odds of having a hearing impairment by 13% in men and 6% in women. In other words, in the population under study, decreased rates of hearing impairment appear to correlate with more recent dates of birth. Although this could partially reflect differences in noise exposure between birth cohorts, it also suggests that as a result of population-wide changes in medical care, nutrition, and general health, present-day adults may be retaining good hearing longer than previous generations. If this is truly the case, then it would be inappropriate to apply aging tables developed more than 40 years ago to estimates of the current burden of NIHL in the population.

2.3 Estimates of the Number of Noise-Exposed Persons

A key method in many estimates of the public health importance of NIHL has been to calculate the approximate size of the population that is exposed to potentially dangerous levels of noise. Usually such estimates have focused on working populations and occupational noise exposure. In 1981, OSHA estimated that 7.9 million manufacturing workers were exposed to noise at daily levels at or above 80 dBA, while the U.S. Environmental Protection Agency (U.S. EPA) in the same year determined that nine million U.S. workers, mostly in manufacturing or utilities industries, were exposed through their occupation to noise levels in excess of 85 dBA (NIOSH 1998). Apparently, there have been no comparable surveys of U.S. workers in recent decades; thus, any current estimates of the burden of NIHL must continue to rely on these probably outdated data. At the same time, some recent studies clearly suggest that a large segment of the U.S. population reports past or present occupational noise exposure. Tak et al. (2009) analyzed 1999–2004 data from the National Health and Nutrition Examination Survey (NHANES) to determine the prevalence of occupational exposure from self-report. They found that 22 million workers (17% of the population-weighted survey) reported exposure to hazardous occupational noise, and among these, 34% reported nonuse of hearing protective devices (HPDs).

Also notable about most estimates of noise-exposed persons used to determine the burden of hearing loss due to noise is that they fail to approximate meaningfully the size of the population exposed to potentially damaging noise outside of work. These noise sources include firearms; power tools; motorcycles, snowmobiles, and other loud vehicles; and amplified music listened to at concerts, nightclubs, or through personal music players. For many of these sources, noise surveys have documented sound levels in a range in which even relatively brief exposures could be damaging over time. Yet rigorous epidemiological studies measuring either the true prevalence of potentially damaging nonoccupational noise exposures or their associations with documented hearing loss remain scarce and sometimes contradictory. For example, the association between reported recreational firearm use and adult hearing loss has been shown in a number of studies (Beckett et al. 2000), but the degree of hearing loss risk from amplified music, although much discussed, especially with reference to adolescent age groups, remains controversial (Zhao et al. 2010). In a study of construction apprentices, Neitzel et al. (2004) found that when compared with the high levels of occupational noise to which they were exposed, nonoccupational noise exposures presented little additional exposure for most workers, although they may contribute significantly to overall exposure in the subset of workers who frequently engaged in noisy activities. Recent studies suggesting increased rates of hearing loss in adolescents have focused greater attention on these issues (Shargorodsky et al. 2010a), and further studies may confirm that the risk of nonoccupational noise exposure is greater than previously believed. In the meantime, any use of occupational noise exposure estimates alone to calculate the burden of NIHL on the U.S. population will inevitably neglect the impact of nonoccupational noise because this impact remains largely unknown.

2.4 Estimates of the Prevalence of Occupational NIHL

In 1972, NIOSH assessed the excess risk of material hearing impairment (defined as binaural average threshold levels in excess of 25 dB HL at 0.5, 1, and 2 kHz) for persons exposed to noise over a 40-year working lifetime as 3% at 80 dBA, 15% at 85 dBA, and 29% at 90 dBA. OSHA used these estimates to set an action level for hearing conservation programs at 85 dBA and a permissible exposure for noise of 90 dBA (OSHA 1983). This type of risk assessment has been part of some estimates of the prevalence of occupational NIHL.

The World Health Organization (WHO) bases many of its public health decisions and policies on studies of the global burden of illness caused by particular diseases or hazards (Terry and Rijt 2010). Applying this approach to occupational NIHL, Nelson et al. (2005) used NIOSH estimates of the prevalence of noise exposure adjusted by data on the distribution of the workforce by occupational category and economic sector, and economic activity rates in each WHO subregion. They defined disabling hearing loss according to WHO criteria as hearing thresholds of greater than 41 dB HL, and extrapolated the risk due to noise from studies of U.S. and British populations. Using these estimates for the worldwide population exposed to noise and the risk of NIHL loss due to such exposure, Nelson et al. (2005) calculated estimates of the attributable fraction (AF) of adult-onset hearing loss resulting from occupational noise exposure. They then applied AFs to WHO estimates of total disability adjusted life years (DALYs) from adult-onset hearing loss to estimate the DALYs due to occupational noise. This modeling exercise found that occupational noise accounts for 16% of the disabling hearing loss in adults (more than four million DALYs), with estimates of disease burden ranging from 7% in developed countries to 21% in underdeveloped and developing WHO subregions. The estimate of the effect of occupational noise on hearing loss burden was greater for males than for females in all subregions. Although this study helped bring NIHL in line with other occupational diseases causing disability worldwide (Driscoll et al. 2005), the analysis failed to consider the impact of lesser degrees of hearing loss, as well as the public health effect of nonoccupational noise.

Dobie (2008), in an alternative analysis, also attempted to estimate the burden of occupational NIHL, and to compare this impact to that of age-related hearing loss. This study considered hearing impairment as a continuous variable, using the AMA hearing impairment criteria of average thresholds at 0.5, 1, 2, and 3 kHz of greater than 25 dB HL with the percentage monaural hearing impairment (MHI) calculated as 1.5% × the pure tone average at 0.5, 1, 2, and 3 kHz – 25 (PTA5123 – 25). Using U.S. Census data, Dobie divided the U.S. population into subgroups based on age, gender, and occupational noise exposure, using NIOSH/OSHA estimates of the size of the noise exposed working population (see earlier). For each subgroup, the burden of hearing loss, in "units of hearing impairment" (UHI), was estimated as the product of MHI and the number of persons in the subgroup. Using these methods to model burden of hearing loss, Dobie (2008) found a result similar to that of the WHO study: that less than 10% of the burden of hearing loss in the United States was due to occupational noise. He concluded that scientific efforts to explore possible preventive treatments for presbycusis such as the role of folate supplementation (see Shargorodsky et al. 2010b) might have a far greater impact on the burden of hearing loss in the United States compared to efforts to reduce noise exposure. Again, as in the WHO analysis, Dobie did not consider either the impact of nonoccupational noise exposures on the population risk of hearing loss or the possible health impact of hearing loss below the level of AMA impairment or occurring at high frequencies (such as 4 kHz) not included in AMA impairment calculations. He also relied, as did the WHO study, on older estimates of both the size of the noise-exposed working population, as well as the expected hearing loss due to aging.

Other smaller studies suggest that the impact of NIHL may be greater than estimated by Nelson et al. (2005) or Dobie (2008). In a Michigan telephone survey study of active surveillance for hearing loss and occupational NIHL using questions added to the U.S. Centers for Disease Control and Prevention (CDC) Behavioral Risk Factor Surveillance System (BRFSS), a high prevalence of self-reported hearing loss was found (44% of respondents ages 75 or older; Stanbury et al. 2008). In that study, approximately 30% of persons whose hearing loss began at age 16 or later associated the hearing loss with occupational noise exposure (Stanbury et al. 2008). A Michigan occupational health surveillance initiative asking audiologists and otolaryngologists to report cases of work-related cases of NIHL identified 1,378 cases between 1992 and 1997, producing evidence that the number of patients with identified occupational NIHL is likely a gross underestimate of the prevalence of the disease (Reilly et al. 1998). Finally, in another study of NHANESIII data, Tak and Calvert (2008) found evidence of hearing difficulty in 11% of individuals ages 18–65, and based on questionnaire responses estimated that 24% of this hearing loss could be attributed to occupational noise, a much higher proportion than found by either the WHO or Dobie analyses. Although this study was limited by its basis in self-reports, the possibility remains that the true burden of illness from occupational noise exposure alone is greater than the modeling studies would suggest.

2.5 Estimates of the Prevalence of Nonoccupational NIHL

As mentioned previously, much of the work to date assessing the public health impact of NIHL has focused on the occupational setting. The true extent of noise effects in the general population remains poorly understood. Niskar et al. (2001) studied audiograms of children and adolescents in the NHANESIII survey, and reported that among U.S. children 6–19 years old, 12.5% (~5.2 million) had evidence of audiometric notching suggestive of NIHL. Similarly, a study of audiograms of young adults ages 17–25 entering an industrial workforce found that 16% showed evidence of high-frequency hearing loss at noise-sensitive frequencies, and that even in these young adults, the risk increased with each year of age (Rabinowitz et al. 2006b). At the same time, the rates of high-frequency loss were not increasing over a two-decade period, suggesting that although NIHL may be a widespread problem, it may not be increasing among young people today compared to previous generations, despite increasing use of personal music players and other electronic devices (Rabinowitz et al. 2006b). These studies of young people before entry into the workforce indicate, however, that nonoccupational noise exposure plays a significant role in the overall burden of hearing loss in the population. As further studies are performed, the widespread hearing losses that some have predicted in adolescents due to noise exposure may yet materialize. For example, a recent analysis comparing hearing thresholds of adolescents in the 1988–1994 and 2005–2006 NHANES surveys found that the prevalence of hearing loss increased from 14.9% to 19.5%, often involving the higher (noise-sensitive) frequencies (Shargorodsky et al. 2010a).

2.6 Estimates of the Severity of NIHL

As Table 2.1 depicts, the public health impact of a condition involves both the condition's prevalence and the severity. It is clear that, as a medical disorder, hearing loss can affect the quality of life for adults (Dalton et al. 2003). Conventional measures such as the AMA impairment calculations may not capture all of the true morbidity of NIHL. To begin with, NIHL may start to affect overall function at a younger age than age-related loss, and the overall impact of hearing loss in a younger, more active person may be relatively greater than in an older person, such as the impact on learning and communication at work, although this has not been extensively studied. However, one aspect of this premature loss could be the effect of NIHL on risk of accidents in a working age population. Recent studies suggest that NIHL does indeed predispose an individual to the risk of work-related accidents. One such study in British Columbia found that the severity of hearing impairment, calculated as average bilateral hearing threshold levels at 3, 4, and 6 kHz, increases the relative risk of single and multiple work accident events when threshold levels exceed 15 dB HL (Girard et al. 2009). Girard et al. also suggested that loss at audiometric frequencies not included in AMA impairment definitions (such as 4 and 6 kHz) and subtle loss with hearing thresholds less than 25 dB HL can have a significant impact on functioning in working adults, neither of which condition is considered by the Nelson et al. (2005) or Dobie (2008) models of disease burden due to NIHL.

Despite such evidence of the impact of NIHL on younger persons, a review of the published literature reveals that there have been very few studies assessing the true severity and cost of illness of NIHL on individuals. Consequently, current estimates continue to rely on crude measures such as the cost of a worker's compensation claim (Bertsche et al. 2006) or the AMA impairment percentages. Another unknown in the determination of the severity of NIHL as an illness is whether the hearing loss caused by noise damage has any different impact on an individual than the loss due to presbycusis. For example, does a noise-damaged ear process speech or other stimuli differently than an ear affected by presbycusis, with the same audiometric thresholds? (For discussion, see Shrivastav, Chap. 7). The severity of NIHL as a medical condition therefore remains an area for further research and policy discussion, which could add to our understanding of the impact of NIHL on health and function.

One basic dogma that drives current assessment of the impact of NIHL (in addition to the assumption that the effects of noise and aging are additive) is that noise damage stops when noise exposure stops. In other words, according to this dogma, noise damage to the cochlea does not predispose the ear to lose hearing at a faster rate once the person leaves the noisy environment (ACOEM Noise and Hearing Conservation Committee 2003). If, however, noise exposure early in life does change the natural history of the aging ear process and contributes to accelerated loss later, the real impact of NIHL on hearing loss rates would be much greater than currently thought. Several studies in animals suggest this effect of prior noise on subsequent hearing loss could occur in some mammalian species, possibly including humans, which would be a disturbing outcome if confirmed. Specifically, Kujawa and Liberman (2009) reported that a detailed histological examination of the ears of mice exposed to noise levels that caused moderate (~40 dB) temporary hearing loss (which was completely reversible) revealed acute loss of afferent nerve terminals and delayed degeneration of the cochlear nerve. These outcomes provide one potential explanation for the increased age-related changes observed in an earlier study in which mice that were exposed to temporary threshold shift inducing noise were subsequently allowed to age (Kujawa and Liberman 2006). Human epidemiological evidence to support such an acceleration of hearing loss as a result of prior noise exposure remains inconclusive. Gates et al. (2000), in an examination of audiograms of older individuals in the Framingham Study, found that those with evidence of noise notches appeared to have accelerated rates of high-frequency loss over time compared to individuals without such noise notching, but few studies have confirmed this finding. As further research explores the relationship between the size of the temporary threshold shift and the later impact on hearing during aging, as well as the extent to which this translates from rodents to humans, it could radically change our assessment of the long-term impact of noise exposures on the auditory system, and the relative importance of noise and aging in the development of acquired sensorineural hearing loss.

2.7 Future Trends

The lack of certainty in estimates of the current public health impact of NIHL makes it even more difficult to speculate about whether NIHL is increasing or decreasing in importance. However, a few trends are worth noting as areas for future attention. Rapid changes in communication technology are placing new demands on an individual's speech perception abilities, such as hearing a cell phone ring or conducting a conversation in the presence of background noise. The impact of noise-induced cochlear damage on these communication settings may be greater than currently appreciated. In addition, the pace of globalization has increased the amount of communication taking place between persons with multilingual backgrounds, who often need to communicate in a language other than their own first language. There is some evidence that persons communicating in a second language, such as English as a second language for native Spanish speakers, may be more likely to report speech communication difficulties at a given level of hearing loss than native English speakers (Rabinowitz et al. 2005).

3 Summary

Hearing loss is one of the most common chronic conditions in adults (Cruickshanks et al. 1998), and yet it often fails to receive the recognition it deserves, often remaining underdiagnosed and undertreated by healthcare professionals (Bogardus et al. 2003). NIHL, as a subset of hearing loss in general, is also likely to be overlooked. It appears to be a condition that is quite prevalent, but that often exhibits only a mild degree of severity. As such, it may have a significant public health importance but be susceptible to routine underestimation. Attempts to assess the public health impact of NIHL have focused on occupational noise-exposed persons and have used measures of hearing impairment that may not capture the true burden of disease in the general population. Evidence that the U.S. population as a whole may be experiencing less age-related hearing loss than in previous generations suggests that the relative importance of NIHL versus presbycusis may actually be increasing, and that the use of standard tables based on populations norms of 50 years ago to adjust audiograms for the effect of aging may not be appropriate in the future. Provocative new research findings suggest that noise exposure may exert greater long-term damage on the cochlea than previously thought, and that the impact of NIHL on accident risk and other functional abilities in younger adults may be significant. If such findings are confirmed with further study, it will further force a reappraisal of the public health significance of NIHL.

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Noise-Induced Hearing Loss
Scientific Advances
Le Prell, C.; Henderson, D.; Fay, R.R.; Popper, A.N.
(Eds.)
2012, XIV, 378 p., Hardcover
ISBN: 978-1-4419-9522-3