Article published online: 2023-08-03

Preventing Occupational Hearing Loss: 50 Years of Research and Recommendations from the National Institute for Occupational Safety and Health

Christa L. Themann, M.A., CCC-A,[1]
Elizabeth A. Masterson, Ph.D., CPH, COHC,[2]
Jeffrey Shawn Peterson, MS:EE,[3] and
William J. Murphy, Ph.D., M.S., M.Eng.[1,4]

ABSTRACT

For more than 50 years, the National Institute for Occupational Safety and Health (NIOSH), part of the United States (U.S.) Centers for Disease Control and Prevention (CDC), has been actively working to reduce the effects of noise and ototoxic chemicals on worker hearing. NIOSH has pioneered basic and applied research on occupational hearing risks and preventive measures. The Institute has issued recommendations and promoted effective interventions through mechanisms ranging from formal criteria documents to blogs and social media. NIOSH has conducted surveillance and published statistics to guide policy and target prevention efforts. Over the past five decades, substantial progress has been made in raising awareness of noise as a hazard, reducing the risk of occupational hearing loss, improving the use of hearing protection, and advancing measurement and control technologies. Nevertheless, noise remains a prevalent workplace hazard and

[1]Noise and Bioacoustics Team, National Institute for Occupational Safety and Health, Cincinnati, Ohio; [2]Division of Field Studies and Engineering, National Institute for Occupational Safety and Health, Cincinnati, Ohio; [3]Pittsburgh Mining Research Division, National Institute for Occupational Safety and Health, Pittsburgh, Pennsylvania; [4]Stephenson and Stephenson Research and Consulting, LLC, Batavia, Ohio.

Address for correspondence: Christa L. Themann, M.A., CCC-A, Noise and Bioacoustics Team, National Institute for Occupational Safety and Health, 1090 Tusculum Avenue, MS C-27, Cincinnati, OH 45226 (e-mail: CLT6@cdc.gov).

The National Institute for Occupational Safety and Health: Occupational Hearing Loss; Guest Editors, Elizabeth A. Masterson, Ph.D., CPH, COHC and William J. Murphy, Ph.D., M.S., M.Eng.

Semin Hear 2023;44:351–393.
Thieme Medical Publishers, Inc., 333 Seventh Avenue, 18th Floor, New York, NY 10001, USA
DOI: https://doi.org/10.1055/s-0043-1769499.
ISSN 0734-0451.

occupational hearing loss is still one of the most common work-related conditions. NIOSH continues to work toward preventing the effects of noise and ototoxicants at work and has many resources to assist audiologists in their hearing loss prevention efforts.

KEYWORDS: NIOSH, history, noise exposure, occupational hearing loss, hearing loss prevention, hearing protection, surveillance, ototoxicity

Imagine if millions of adult-onset hearing losses could be prevented. This is entirely possible. It is what researchers at the National Institute for Occupational Safety and Health (NIOSH), part of the United States (U.S.) Centers for Disease Control and Prevention (CDC), have been working toward for over 50 years. It is what both the American Speech Language Hearing Association (ASHA)[1] and the American Academy of Audiology (AAA)[2] consider an essential aspect of audiology practice. It is preventing hearing loss from hazardous noise and other ototoxic exposures.

Noise exposure is the leading cause of preventable hearing loss among adults.[3,4] While noise occurs in many aspects of daily life, workplace noise is generally more intense and more prolonged than noise encountered off the job.[5] Studies have shown that non-occupational noise contributes only minimally to overall exposures for most workers who have noisy jobs.[6,7] NIOSH estimates that 22 million U.S. workers are exposed to hazardous noise on the job each year, and approximately 25% of the U.S. workforce has a history of occupational noise exposure.[8] About 58% of self-reported hearing difficulty among workers can be attributed to workplace noise.[8] Worldwide, an estimated 16% of the cases of moderate or worse (> 40 dB HL) hearing loss in adults are attributable to occupational noise exposure.[9] In addition to hearing loss, hazardous noise can lead to other auditory outcomes (e.g., tinnitus, hyperacusis) and has been associated with a number of nonauditory outcomes (e.g., cardiovascular disease, fatigue) as well.[10] Some occupational chemical exposures (e.g., solvents, heavy metals) can also lead to hearing trouble, either alone or in combination with exposure to noise.[11]

Established by the Occupational Safety and Health Act of 1970, NIOSH has conducted research and published recommendations to promote worker health and safety for over 50 years.[12] From its inception, NIOSH has had an active research program focusing on reducing occupational noise and its effects.[13] Specific research areas and program priorities have changed over time as workplaces changed, technologies improved, certain issues resolved, and new questions emerged. Some early recommendations for protecting worker hearing have remained in place through this day, while others have evolved as knowledge grew and better approaches became evident. One constant through it all has been the mission of the noise research program "to provide national and world leadership to reduce the prevalence of occupational hearing loss."[14]

This article will trace the history of the NIOSH noise and hearing research program over the past five decades—summarizing major activities, discussing current focus, and looking toward the future. The focus will be almost exclusively on the NIOSH intramural research program. NIOSH also has a diverse portfolio of extramural research—including investigator-initiated research grants, mentored career development awards, small business innovation research projects, and training programs. In addition, NIOSH supports education and research centers and state surveillance programs which contribute to and extend the impact and reach of NIOSH research. The NIOSH extramural program has funded many investigations of occupational noise and hearing loss throughout its history which have contributed substantially to protecting worker hearing. The current extramural portfolio can be viewed on the NIOSH web page (https://www.cdc.gov/niosh/oep/performance.html#ActiveAwards), along with annual reports (http://www.cdc.gov/niosh/oep/

performance.html) highlighting activity and impact. Abstracts of completed funded research are available on NIOSHTIC-2 (https://www.cdc.gov/niosh/nioshtic-2/20000062.html), the NIOSH bibliographic database which maintains records of all publications, documents, reports, and products developed with NIOSH support.

In view of the place which both ASHA and AAA assign to hearing loss prevention within the scope of audiology practice, this review will give particular attention to the relevance of NIOSH research for clinical audiologists. NIOSH resources that are available to support hearing loss prevention efforts will be highlighted.

BEFORE NIOSH: FOUNDATIONS

The U.S. government launched efforts to improve worker safety and health early in the 20th century, following several occupational disasters (e.g., the Monongah Coal Mine explosion, the Triangle Shirtwaist Factory fire) which cost hundreds of lives.[15,16] Although noise had long been recognized as a workplace hazard, early efforts to study and control it were limited due to the lack of equipment to accurately quantify noise levels or measure their effect on hearing.[17] By the mid-20th century, however, sound level meters (SLMs)[17] and audiometers[18] had been developed to the point of being commercially available. An early study of noise in industry estimated that 50% of industrial machinery produced sound levels in excess of 90 decibels (dB) sound pressure level (SPL) and concluded that no manufacturing facility was free of noise problems.[19] A landmark court decision in 1948 compensated a noise-exposed worker for hearing damage sustained on the job, legally establishing noise-induced hearing loss (NIHL) as an occupational disease.[19]

In 1950, the U.S. Public Health Service (PHS) established a Field Headquarters for its Division of Industrial Hygiene in Cincinnati, Ohio.[20,21] This unit—an early precursor to NIOSH—conducted studies on workplace noise exposure, both in the laboratory and in the field. Laboratory research investigated the influence of various noise parameters on hearing loss risk, the effect of noise exposure on performance, and other physiological and psychological factors associated with noise exposure, including annoyance. Field investigations focused on identifying specific noise sources through overall industrial hygiene surveys, designing potential controls, estimating the number of workers exposed to hazardous noise across various industries and occupations, and measuring the relationship between noise exposure and hearing loss with an eye toward developing criteria for safe exposures. This latter effort involved both longitudinal and cross-sectional hearing surveys.[22]

One of the longitudinal studies conducted by the Division of Industrial Hygiene was done in federal penitentiaries, which operate manufacturing facilities to provide opportunities for inmates to learn new skills and earn an income. Noise levels ranged from < 80 dB to 104 dB SPL across the industries and were classified as constant, intermittent, or impulsive. Inmates who worked in quiet prison areas participated as a control group. A unique aspect of studying this population was the ability to fully assess off-work noise exposures. The study included approximately 1,600 men. Key findings included identification of the characteristic "notch" in audiometric thresholds around 4,000 Hertz (Hz) and the rapid development of NIHL in the initial months of exposure.[23,24]

Division of Industrial Hygiene cross-sectional noise and hearing surveys were accomplished across multiple industries, often triggered by requests from workplaces concerned about potential noise hazards.[25] In 1968, the various studies of noise and hearing coalesced into an organized research effort known initially as the National Noise Study. The study aimed to systematically collect noise and hearing data across a variety of industries and a broad cross-section of workers to establish a criterion for exposure that could be applied to general industry. Solicitations for volunteer companies to participate in the study were made through industrial hygiene conferences and regional PHS offices. Worksites were selected to participate based on the nature and level of noise hazards and the range of years of exposure among employees. Noise and medical histories were obtained from all participants. Otoscopy

Figure 1 Audiometric testing van used to conduct some of the early studies of hearing loss due to occupational noise exposure.

and audiometry were conducted in a specially equipped audiometric test van (Fig. 1). Employees were tested at the beginning of their work day to avoid contamination by temporary threshold shifts. Non–noise-exposed workers were recruited from the same plants to serve as a control group. Ultimately, data were collected from 3,699 workers at 13 companies. These data would become the basis of the initial NIOSH recommendations regarding noise exposure.[26]

By 1970, the PHS Division of Industrial Hygiene had grown into the Bureau of Occupational Safety and Health, located within the Environmental Control Administration of the U.S. Department of Health, Education, and Welfare.[20,25] The political landscape was being shaped by a growing awareness of the effects of environmental exposures on health. A 1965 PHS report linking workplace chemical exposures to cancer brought increased attention on occupational hazards and led to a call for a more comprehensive national program to address them.[15] On December 29, 1970, the Occupational Safety and Health Act was signed into law and NIOSH was born.[12]

1970s: DEFINING THE PROBLEM AND ESTABLISHING RECOMMENDATIONS

NIOSH officially opened its doors on April 28, 1971—the effective date of the legislation which created it. The 1969 military draft lottery enabled NIOSH to recruit a number of talented young scientists to fulfill their service obligation as officers in the U.S. Public Health Service Commissioned Corps (a nonmilitary uniformed service), which helped staff the Institute quickly (Terrence L. Henderson, e-mail communication, February 2022). The former Bureau of Occupational Safety and Health was transformed into NIOSH; therefore, much of NIOSH research in its early years—including the noise and hearing research—was based in Cincinnati, OH.[20]

By Congressional mandate, NIOSH was charged with developing recommended occupational health and safety standards, conducting research across the breadth of occupational hazards, providing training for occupational health and safety professionals, and consulting with employers, employees, and organizations representing them on effective methods of preventing occupational illnesses and injuries.[12,20,27] NIOSH was designed to operate independently of the Occupational Safety and Health Administration (OSHA—the regulatory agency established by the same Act), to ensure that its research would be objective and scientific.[27] OSHA was placed administratively in the Department of Labor, while NIOSH remained in the Department of Health, Education, and Welfare (now the Department of Health and Human Services) and eventually became one of the agencies in the Center for Disease Control (now the Centers for Disease Control and Prevention—CDC).

The first decade of NIOSH focused on reorganizing and expanding to meet its new responsibilities. To establish research priorities, NIOSH launched the National Occupational Hazard Survey (NOHS) to gather information on the safety of working conditions and identify key areas in need of intervention. The survey collected data from 985,000 workers across a representative sample of more than 4,600 manufacturing and nonmanufacturing worksites.[20,28] The protocol included noise measurements made near the worker's ear, noting whether the exposure included impact noise (defined as peaks exceeding 130 dBC [C-weighted decibels] occurring more than 1 second apart).[29] NOHS results indicated that more than 7.5 million workers were exposed to noise levels of 85 dBA (A-weighted decibels) or more, including 23% of manufacturing workers.[28] Noise exposure was clearly a priority for the new Institute. With an existing noise research program carried over from the Bureau, NIOSH was ready to address it.

Noise Criteria Document

NIOSH placed a major emphasis in its first few years on producing "criteria documents" to guide the development of appropriate workplace regulations. The Noise Section developed recommendations on noise exposure based on data from the National Noise Study which NIOSH continued, changing its name to the Occupational Noise and Hearing Survey (ONHS). By 1972, data had been collected from a broad swath of industries and occupations, ranging from steel fabrication to trucking and press operators to toll collectors. Distributions of hearing thresholds by age and exposure level were determined and plotted in a way that emphasized the raw data over parametric modeling to illustrate the range of losses experienced by workers (Fig. 2). Percentages of workers developing hearing impairment were calculated (binaural pure tone average thresholds > 25 dB at 500, 1,000, and 2,000 Hz and at 1,000, 2,000, and 3,000 Hz). Based on the threshold averages measured in workers exposed for various periods of time, NIOSH aimed to establish an exposure limit that would protect against developing a degree of hearing loss that would interfere with understanding speech among workers exposed to noise over a 40-year career.[26,30]

The NIOSH criteria document set the recommended exposure limit (REL) for noise at 85 dBA, calculated as a time-weighted average (TWA) over 8 hours, using a 5-dB exchange rate (i.e., allowing exposure to increase by 5 dB with each halving of exposure time).[30] Acknowledging the challenges involved in reducing noise levels at existing facilities, the REL was meant to apply to new facilities and a temporary REL of 90 dBA was permitted for existing noisy worksites to give them time to implement engineering controls. The criteria document made additional recommendations to protect workers exposed above the REL, including notification of exposure, audiometric monitoring, hearing protection, and training.[30] It also included a set of "age correction" tables based on audiometric data from the non–noise-exposed workers who served as the control group in the ONHS. These tables were designed to account for the effects of aging on hearing and eventually became codified in the OSHA noise exposure regulation,[31] though as time went on NIOSH developed better approaches for considering the effects of aging among noise-exposed workers.[32,33]

Survey of Hearing Conservation Programs in Industry

Having made recommendations in the criteria document for protecting the hearing of workers whose exposures exceeded the REL, NIOSH launched a survey of workplaces with hazardous noise levels to assess how well companies were able to implement these recommendations in

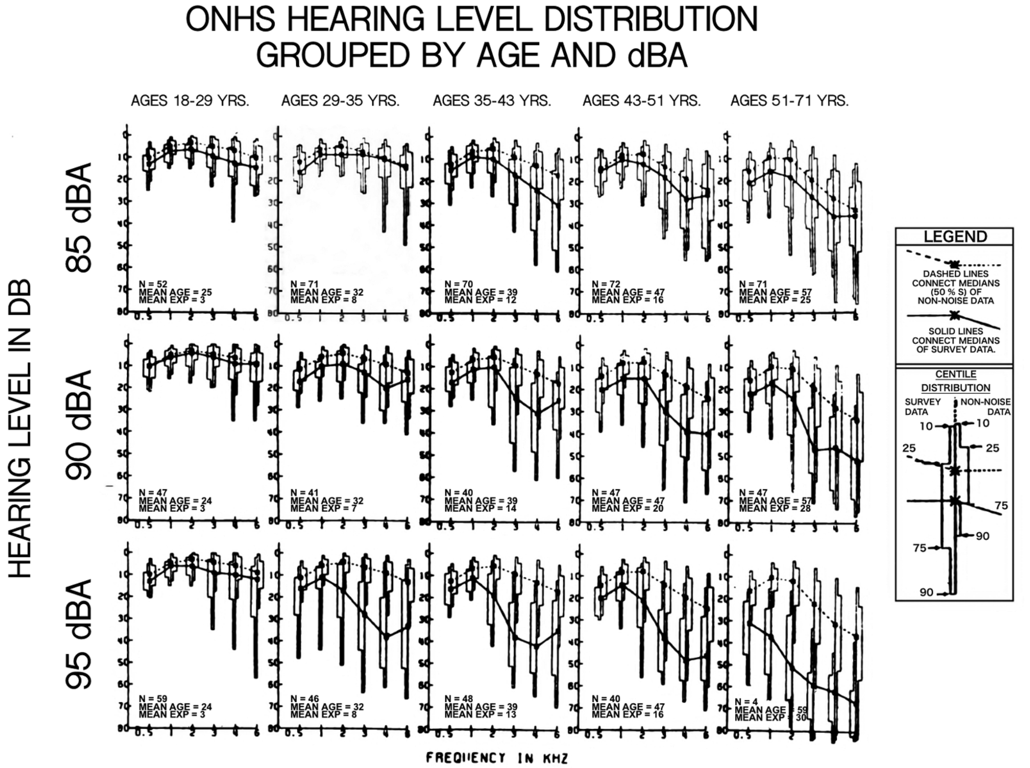

Figure 2 Summary of results from the 1968–1972 Occupational Noise and Hearing Survey which formed the basis of the original NIOSH criteria document on noise exposure.

practice. The first part of the survey involved a mailed questionnaire to companies in the manufacturing, mining, construction, and transportation industries expected to have high levels of workplace noise. The mail survey was followed by on-site visits to a subset of responding businesses (excluding construction) which reported having a hearing conservation program in place for at least 5 years.

Results indicated that many companies had difficulty implementing engineering controls due to lack of funds and/or technical expertise. This finding prompted NIOSH to develop resources to assist with noise control (see next section). Survey results also indicated serious problems with audiometric testing programs for noise-exposed workers. Among the workplaces visited in the on-site portion of the study, 80% did not meet audiometer calibration and/or background noise standards.[34] These findings prompted NIOSH to support the formation and first-year operation costs of a certifying board for industrial hearing technicians through an organization that is currently known as the Council for Accreditation in Occupational Hearing Conservation.[35]

Noise Control

NIOSH advocates a hierarchy of controls that prioritizes eliminating or reducing the hazardous exposure (e.g., through engineering controls) over relying solely on personal protective equipment (e.g., hearing protectors).[36] Noting the difficulties that companies reported with implementing effective noise control solutions, NIOSH published the *Industrial Noise Control Manual* in 1975. The manual provided practical guidance on noise control techniques as well as multiple case study examples of noise control projects which had successfully reduced sound levels in various industrial plants.[37] An updated version of the manual was published in 1978.[38] In conjunction with the *Industrial Noise Control Manual*, NIOSH assembled a compendium of commercial noise reduction materials and systems as a reference for those engaged in noise control.[39] This compendium was updated and republished in 1980.[40]

NIOSH continues to advocate engineering controls as the primary means of reducing worker noise exposure. As the principles of noise control engineering have remained constant over time, the general concepts described in the *Industrial Noise Control Manual*[37,38] and the *Compendium of Materials for Noise Control*[39,40] are still useful for noise control engineers today. A subset of the noise control solutions described in these early documents have been republished on the NIOSH website.[41] Although noise control sometimes can be complicated and expensive, it does not always have to be. Often the simple approaches illustrated in these guides, such as moving equipment away from reflective surfaces or replacing metal parts with plastic or rubber parts, can substantially lower noise levels, reducing or eliminating the risk to worker hearing.

Hearing Protection

Despite the preference for noise control over personal protective equipment, NIOSH recognized from the outset that hearing protection devices (HPDs) would be necessary in some circumstances to protect worker hearing. In response to requests for information about HPDs, NIOSH first published a list of available devices in 1973. A revised and expanded list of hearing protectors was published in 1975 which included manufacturer-supplied data on the attenuation characteristics of each device across frequency bands. This updated document included three methods for calculating an overall noise reduction factor from the octave-band attenuation data to assist in selecting devices that would reduce workplace noise levels (measured in dBA) sufficiently.[42] The list was updated again and published as the *Compendium of Hearing Protection Devices* in 1984[43] and 1994[44] and then converted from a print document to an online resource in 2003. In 2018, NIOSH discontinued updating the hearing protector compendium, as the most up-to-date information on individual HPDs is now readily available on manufacturers' websites.

A standard approach for measuring the attenuation of HPDs across frequencies was developed by the American Standards Association (ASA) in the 1950s and used by the majority of HPD manufacturers at the time NIOSH was established.[45] The standard used an approach known as real-ear attenuation at threshold (REAT) in which hearing thresholds are measured in test subjects across various frequencies with and without hearing protectors in place. The threshold differences at each frequency indicate the attenuation provided in that octave band.[42] However, as noted earlier, a measure of overall noise reduction was desirable to simplify device selection. Following the passage of the 1972 Noise Control Act, the U.S. Environmental Protection Agency (EPA), Office of Noise Abatement and Control (ONAC), was tasked with developing regulations to label devices that reduced noise, including hearing protectors. NIOSH scientists collaborated with ONAC to develop the three methods to characterize the performance of HPDs that were published in the 1975 NIOSH list of hearing protectors.[42] The EPA selected NIOSH Method No. 2 as the Noise Reduction Rating (NRR), and mandated that all hearing protectors manufactured for sale in the United States be labeled with an NRR.[46] OSHA codified the NRR in the estimate of worker noise exposure with the promulgation of the Hearing Conservation Amendment in 1983.[31] Thus, although much has been learned about drawbacks to the NRR in the years since it was developed and standards for measuring hearing protector attenuation have been updated multiple times, the NRR remains the labeling standard for HPDs in the United States today.

One shortcoming of the NRR that became apparent very early is that the performance of HPDs when fitted in the laboratory is far different from what is achieved in the real world. Between 1977 and 1981, NIOSH conducted a series of field studies to investigate how the attenuation of earplugs as worn by workers on a daily basis compared to the attenuation measured in a laboratory according to the ASA standard. NIOSH contracted Paul Michael and his associates at the Pennsylvania State University to develop a hearing protector "fit-test" system, which used transducers mounted in a modified large volume earmuff to deliver test signals in a manner equivalent to the laboratory method. The system required a rack of

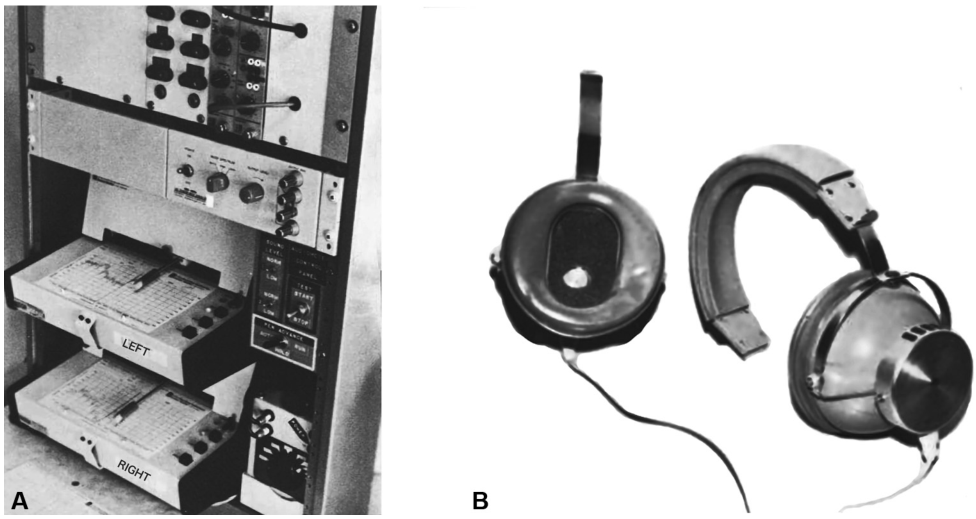

Figure 3 Hearing protector fit-testing system developed for the studies of real-world hearing protector attenuation from 1977 to 1981. Equipment (**A**) was mounted in a rack in the mobile van. Test signals were delivered through transducers mounted into modified large volume earmuffs (**B**) which did not interfere with the earplug fit. (Reprinted with permission from Edwards et al.[48])

equipment and was installed in a mobile van (Fig. 3).[47]

Over 400 workers from 15 industrial plants using eight different types of earplugs participated in the initial NIOSH field studies. Each worker was tested five times. Results clearly indicated that the attenuation measured in the workplace is very different from the attenuation measured in the laboratory. Most workers attained less than half of the attenuation predicted from the laboratory-derived measurements, and some workers received little or no sound reduction from their earplugs. Furthermore, the standard deviations in the worker data were more than twice as large as those from the laboratory data.[48,49] Data from these and similar studies led OSHA to eventually recommend application of a 50% de-rating to the NRR in certain circumstances,[50] and led to other de-rating recommendations over time as well.[32] De-rating is an imperfect solution, however, as it fails to account for the wide variability in attenuation achieved across workers and devices. The field performance of particular HPDs varies broadly even within general categories of hearing protection (see Fig. 4). This is a conundrum NIOSH would re-visit time and time again over the next few decades.

Health Hazard Evaluations

When creating NIOSH, Congress explicitly directed the Institute to "determine following a written request by any employer or authorized representative of employees … whether any substance normally found in the place of employment has potentially toxic effects" and to "consult with and advise employers and employees … as to effective means of preventing occupational injuries and illnesses."[12] NIOSH established its Health Hazard Evaluation (HHE) Program to address this mandate. This important aspect of the Occupational Safety and Health Act enables those who have concerns about a workplace hazard to access the breadth of health and safety expertise at NIOSH at no cost to themselves.[16] Since its inception, the NIOSH HHE Program has conducted noise evaluations in response to nearly 300 such requests,[51] and has provided technical assistance to many more without the need for a site visit. HHE field investigations have identified new or complex noise exposure problems and launched research efforts to address them.

The first HHE field investigation of noise exposure was conducted at the Midwest Steel Corporation in Portage, Indiana. Although the request had been to evaluate a variety of

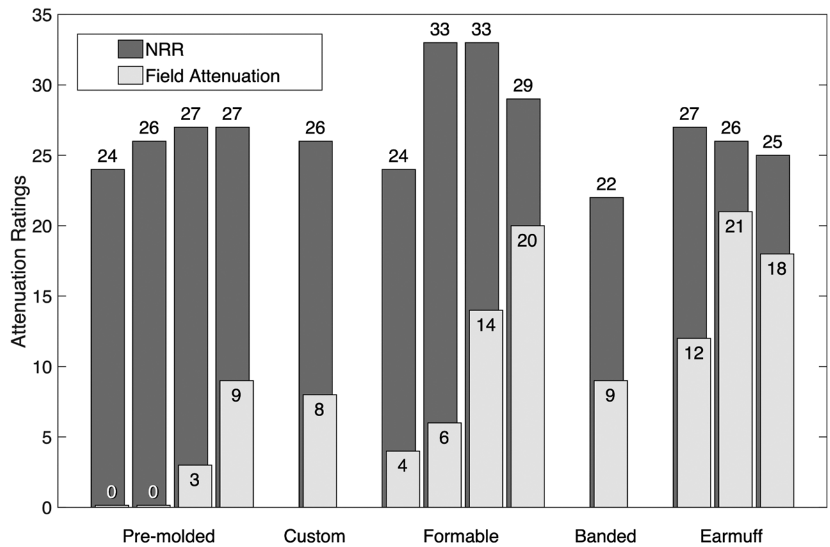

Figure 4 Manufacturers' published Noise Reduction Ratings (NRRs) (dark bars) compared to hearing protector attenuation measured on workers across various NIOSH studies (light bars) for selected hearing protection devices of different types.

chemical exposures along the electrolytic tinning line, NIOSH investigators noted high noise levels which measured 82 to 94 dBA. They made recommendations for noise control and advised the employer to provide hearing protection and audiometric testing.[52] Other early HHEs were done at a variety of manufacturing plants, a newspaper printing facility, a freight railway, and the currency destruction unit of a Federal Reserve Bank.[51] Not all noise-related HHEs were requested due to hazardous exposures. In 1978, a request was received on behalf of reservation clerks for Ozark Airlines in Peoria, Illinois, who were experiencing multiple symptoms of illness of unknown origin. Among the many exposures measured, investigators noted sound levels ranging from 65 to 85 dBA. While not a risk to hearing, these levels were high enough to impair communication, particularly since "the majority of calls handled by the reservationists [were] long distance and subject to line distortions and poor connections." The NIOSH investigators concluded that the stress of communication difficulty in combination with other issues identified in the area were compatible with the complaints reported by the staff. Ozark installed sound dampening partitions between the reservationists, which resulted in an average sound reduction of 10 dBA.[53]

1980s—STREAMLINING SCOPE AND STRATEGIZING PREVENTION

NIOSH entered its second decade having tackled many of the initial tasks assigned to it by the Occupational Safety and Health Act—publishing well over 100 criteria documents, creating educational materials and training opportunities for health and safety professionals, establishing the HHE program, and maintaining the course of research carried over from its Bureau days.[20] This decade saw a shift away from regulation, illustrated by the staying and subsequent revision of the OSHA Hearing Conservation Amendment and the defunding of the EPA Office of Noise Abatement and Control. The momentum that had pushed for a national program of occupational health and safety waned somewhat.[54] The Institute streamlined its operations and refocused its priorities.[20]

From 1981 through 1983, NIOSH conducted another national survey of worker exposures. The National Occupational Exposure Survey (NOES) used the same noise measurement protocol as the NOHS; however, differences in study methods and covered industries prevent directly comparing the results across surveys. Nonetheless, the NOES found that 4.2 million workers were exposed to noise at or above 85 dBA, clearly indicating that hazardous noise was still an issue for U.S. workers.[55,56]

Springboarding off the effort to establish national public health objectives launched in 1979 with the landmark publication of *Healthy People: The Surgeon General's Report on Health Promotion and Disease Prevention*, NIOSH identified 10 leading work-related diseases and injuries on which to focus its efforts.[20] NIHL was among them. NIOSH worked with partners to identify necessary prevention strategies to reduce the effects of occupational noise exposure and published recommendations in *A Proposed National Strategy for the Prevention of Noise-Induced Hearing Loss*. Strategies centered on regulation, research, and information dissemination.[54] These objectives guided the efforts of the NIOSH noise program through the 1980s and beyond.

Mechanisms of Hearing Damage

One of the research recommendations made by the expert panel who developed *A Proposed National Strategy for the Prevention of Noise-Induced Hearing Loss* was to "describe the physiologic mechanisms associated with noise-induced hearing loss … [in order to] clarify which noise parameters contribute the most to damage in the ear."[54] Because research on mechanisms of damage must be accomplished primarily in animal models, NIOSH began a program of animal research to better understand the cascade of events underlying noise damage to the ear. Initial intramural NIOSH research investigated the differential effects of various types of noise exposure. Later studies examined the role of genetics in NIHL, oxidative damage within the cochlea, and ototoxicity.

In 1988, NIOSH published a summary of normal and damaged cochlear morphology.[57] It described the mechanisms of cochlear damage. These include metabolic exhaustion (i.e., a cell's inability to meet the energy demands placed on it due to constant or very intense overstimulation) and mechanical injury (i.e., rupture of the cell or cell junctions due to the physical force of waves set up within the organ of Corti). Damage can also occur through an interaction between the two (i.e., cells under metabolic stress may be more susceptible to physical stress). Scanning electron photomicrographs illustrated areas of common damage within the cochlea, including hair cell loss, hair cell enlargement and deformation, stereocilia breakage or fusion, collapse of supporting cells, and swelling or atrophy within the stria vascularis.

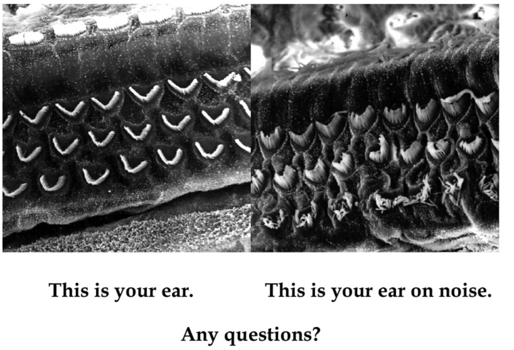

Figure 5 Images of a normal cochlea (left) and noise-damaged cochlea (right) in a play on a popular 1980s antidrug campaign to illustrate the hazards of noise to hearing. (Photos by NIOSH.)

Sometime later, the NIOSH noise team leveraged a popular antidrug commercial launched in the late 1980s to point out the dangers of hazardous noise exposure. Adapting the well-known "This is your brain. This is your brain on drugs"[58] to "This is your ear. This is your ear on noise," images of normal and noise-damaged cochlear hair cells were used in many presentations by NIOSH staff and ultimately made available to other hearing professionals through the National Hearing Conservation Association (Fig. 5).

Impulse/Impact Noise

A major focus of the NIOSH noise research program during the 1980s (and one which continues today) was investigating the hazard posed by impulse/impact noise. Initial studies consistently indicated that brief, high-level sounds such as impulse noise (created by a sudden pressure release or explosion) or impact noise (created by the collision of solid objects) were more damaging to hearing than continuous noise.[59] Developing appropriate exposure limits for this type of noise was plagued by several problems. First, the dose–response relationship between brief, high-level sounds and hearing loss was not clear, reflecting a lack of understanding of the characteristics of impulse/impact noise underlying the increased risk. As these characteristics were not well defined, appropriate metrics for assessing risk were also undefined. An even more basic problem, however, was the difficulty in accurately measuring these sounds in the workplace. NIOSH worked to address all of these issues.

The NIOSH animal noise research program investigated properties of impact noise that affect hearing loss. One key study examined the relative effects of continuous noise and impact noise. Animals in the impact noise group were exposed to a recorded impact of a hammer striking a nail into wood at a rate of 2.26 nails per second, 4 hours per day for 5 days. Those in the continuous noise group were exposed to broadband continuous noise shaped to match the impact noise in both intensity and spectrum for the same time intervals. Auditory brainstem response thresholds were measured pre- and 1 month postexposure by staff blinded to the animals' exposure group. The chinchillas exposed to impact noise exhibited hearing shifts of 20 to 40 dB greater than those exposed to continuous noise, providing evidence that the increased risk to hearing from impulse/impact noise is due to one or more parameters of the impulse or impact itself, rather than differences in energy or spectrum.[60]

NIOSH also investigated the hazard of impact noise in field studies. Through an international collaboration with researchers in Scotland, NIOSH analyzed audiometric threshold data collected from hammer and press operators in the drop forge industry. Hearing thresholds from over 10,000 workers across seven forges were analyzed along with detailed recordings of impacts from presses (110–120 dB peak with 10–15 msec rise times) and hammers (~120–140 dB peak with 100–300 μs rise times). Equivalent continuous noise levels were estimated to be approximately 99 dBA for press operators and 108 dBA for hammer operators. Thresholds of hammer operators were poorer than those of press operators after the age of 35 years, leading the investigators to conclude that differences in rise time and peak level of the impacts did not differentially affect hearing damage until after at least 10 years of exposure. In addition, hearing thresholds for both operators were similar to those predicted based on the calculated equivalent exposure level through 10 years of exposure, after which hearing thresholds were poorer than predicted. Ten years of exposure seemed to be the cut point at which impact noise began to have more adverse effects on hearing than continuous noise of an equivalent level.[61] A more recent NIOSH study of hearing risk among drop forge workers is being published concurrently in this *Seminars in Hearing* issue.[62]

In these initial laboratory and field studies, NIOSH framed measurements of impulse/impact noise in the context of continuous noise (e.g., equivalent sound level). However, the adequacy of steady-state noise descriptors for characterizing impulse/impact noise was questionable, as indicated by the two studies just described. In the mid-1980s, NIOSH proposed a statistical descriptor known as kurtosis as an alternate metric for describing impulse/impact noise.[63] Kurtosis describes the "peakedness" of the distribution of amplitudes measured over a given time period. Kurtosis accounts for all of the peaks in an impulse, the duration of each sound burst, and the repetition rate. Kurtosis also allows mathematical manipulations that enable the level, spectrum, and peak distribution of the noise to be studied individually in relation to their contribution to hearing risk.[63] While the measure showed promise, equipment to measure kurtosis outside of a research environment would not be available for several more decades.

In fact, accurate measurement of any impulse/impact noise metric outside of the laboratory was problematic in the 1980s. SLMs and dosimeters generally incorporated a 1-second time constant (i.e., the "slow" response setting), which averages any noise fluctuation that occurs over a shorter time period and can lead to an underestimation of dose. In addition, the 1-inch microphones often used in the field during this time period do not have sufficient high-frequency response to adequately characterize impulses. NIOSH published recommendations for improving the ability of SLMs and dosimeters to accurately measure impulse/impact noise which it considered achievable at the time—particularly reducing the time constant to less than 30 msec.[64] As years progressed and technology expanded, NIOSH would make additional recommendations to more accurately characterize impulse/impact noise exposures.

National Occupational Health Survey of Mining

The 1977 US Federal Mine Safety and Health Amendments Act mandated that the toxicity of "each toxic material or harmful physical agent which is used or found in a mine" be evaluated.[65] Responsibility for this mandate was assigned to NIOSH and accomplished through the National Occupational Health Survey of Mining (NOHSM), conducted from 1984 to 1989. The survey was modeled on the previous National Occupational Hazard Survey and National Occupational Exposure Survey. However, instead of physically measuring the sound level, surveyors recorded a hazardous noise exposure whenever they had to speak in a raised voice to be heard by someone standing next to them. Surveyors also recorded whether the exposure was full-time (> 4 hour/day on at least 90% of workdays a year) or part-time (> 30 minutes at least once per week during at least 90% of the year) and whether any controls were noted (including hearing protection, isolation, break periods, and other administrative controls).[65] The survey used systematic sampling to project national estimates across 66 mineral commodities. Hazardous noise (either full- or part-time) was noted for 73% of surveyed miners, representing approximately 200,000 workers nationwide. NIOSH used the NOHSM noise data to provide guidance to the Mine Safety and Health Administration (MSHA) regarding regulatory and research priorities.[65]

Some years later, MSHA asked NIOSH to analyze longitudinal audiometric data from over 12,000 miners to determine whether mining noise regulations at the time were sufficiently protective. NIOSH reported that 50% of miners in the database had a mild hearing loss and 20% of miners had a moderate hearing loss by the age of 35 years. By the age of 64 years, 80% of miners showed hearing losses ranging from moderate to profound, posing a potential safety risk due to an inability to hear warning signals and "roof talk" (sounds which can indicate a possible cave-in).[66] In 1999, MSHA updated its mining noise regulation, requiring many of the provisions recommended in the NIOSH criteria document.[67]

Practical Guide

One of the objectives regarding information dissemination recommended in *A Proposed National Strategy for the Prevention of Noise-Induced Hearing Loss* was to "develop and disseminate guidelines that show employers and providers of hearing conservation services how to ensure that their hearing conservation programs are effective in preventing NIHL."[54] Although the 1972 NIOSH criteria document provided recommendations for an effective hearing conservation program and the 1983 OSHA Hearing Conservation Amendment established certain regulatory requirements for hearing conservation programs, the consensus was that employers lacked information on how to build a successful program and workers lacked an understanding of their role in ensuring the necessary protective actions were effectual.[54] To address this need, NIOSH brought together a working group to develop a set of practical guidelines for preventing occupational NIHL. These were published as *A Practical Guide to Effective Hearing Conservation Programs in the Workplace*.[68]

The NIOSH *Practical Guide* outlined seven components of an effective hearing conservation program—noise monitoring, engineering and administrative controls, audiometric testing, hearing protection, education and motivation, record-keeping, and program evaluation. It provided nontechnical guidance for each component tailored separately for employers, workers, and hearing conservation program managers. In addition, the guide advocated integration of hearing conservation efforts into a company's overall health and safety program and identification of a key person (the “program implementor”) to be responsible for all aspects of the program. The guide also included checklists to ensure compliance with OSHA regulations and evaluate the program for effectiveness of practices beyond basic compliance.[68]

The *Practical Guide* has been one of the most successful NIOSH publications on noise and hearing loss. Over 25,000 print copies were distributed. It was updated and republished as *Preventing Occupational Hearing Loss - A Practical Guide* in 1996[36] and later republished again by the National Safety Council. Over 30 years later, it is still downloaded from the NIOSH website approximately 200 times per month (Burton Tienken, e-mail communication, August 2022). The guide is widely used in training hearing conservation professionals, including audiology graduate programs and courses managed through the Council on Accreditation in Occupational Hearing Conservation to certify occupational hearing conservationists.

1990s—NEW DIRECTIONS AND RECOMMENDATIONS

As NIOSH approached its 25th anniversary, evidence indicated substantial improvements in worker health and safety.[69] Workplace fatalities had dropped by 50% since 1970, injuries had declined, and certain occupational illnesses such as byssinosis (brown lung disease) and vinylchloride-induced cancer had been nearly eradicated.[69] These improvements were due in part to actions guided by occupational safety and health research. However—though diminished—the burden of work-related injuries, diseases, and deaths continued, and both the private and public sectors faced fiscal constraints. This landscape led NIOSH to focus on improving coordination with other stakeholders in occupational safety and health. Through a consensus-building process that involved working groups, town hall meetings, liaison committees, and public comment, NIOSH developed the National Occupational Research Agenda to guide research over the next 10 years. The agenda was built on input from scientists, health and safety professionals, workers, employers, labor and professional organizations, and other federal agencies. It identified 21 priority topic areas. Once again, NIHL was among them.[69]

Around this time, NIOSH also gained new responsibilities for mine safety research, which had been previously managed by the U.S. Bureau of Mines.[70] This brought two new laboratories to NIOSH—the Pittsburgh and Spokane Research Centers—and a longstanding program of noise control research in mining.

A Paradigm Shift

The update of the *Practical Guide* just 6 years after its initial publication brought a paradigm shift in the NIOSH approach to reducing the burden of hearing loss among workers in 2 ways. First, NIOSH broadened its view of work-related hearing loss to address other risks to hearing that were becoming evident. Certain chemicals commonly used in manufacturing, mining, construction, agriculture, utilities, and other industries can also damage the ear. NIOSH therefore shifted from addressing NIHL specifically to addressing occupational hearing loss (OHL) to encompass ototoxicants as well as any other hazard which might be shown to affect worker hearing.[36,69]

Second, NIOSH shifted from thinking of “hearing conservation” to focusing on “hearing loss prevention.” The change runs much deeper than mere semantics. Hearing loss prevention emphasizes the fundamental principle that no one should suffer any change in hearing as a result of work. The focus is shifted from conservation of hearing to preventing any hearing loss. It fosters a mindset that values hearing health and creates and promotes a prevention-minded safety climate.[36]

Ototoxicity

Historically, noise exposures and chemical exposures had been considered unrelated occupational risks. The potential for auditory damage was not examined in the process of recommending exposure limits for chemical substances, and potential chemical effects on hearing had not been considered when setting exposure limits for noise. But a few studies during the 1980s began to indicate that certain chemicals might also damage hearing, either alone or in combination with noise. The 1988 *Proposed National Strategy for the Prevention of Noise-Induced Hearing Loss* noted a need to identify potential interactions between noise and other agents in the workplace (e.g., solvents, metals, pharmaceuticals) which could affect hearing.[54]

Much of the work on ototoxicity at NIOSH has been accomplished through extensive international partnerships. A study of petroleum workers in Columbia found hearing loss prevalences of 42 to 50% among workers exposed to both noise and solvents, despite having exposures that were mostly below the recommended limits for each.[71] A study of workers in the fiberglass products industry in Sweden exposed to styrene alone at levels below the exposure limit found significantly poorer high-frequency hearing thresholds than those of nonexposed workers, as well as poorer performance on tests involving the central auditory system (e.g., interrupted speech, speech in noise).[72] A study of insecticide sprayers in Brazil exposed to organophosphate and pyrethroid compounds found signs of central auditory dysfunction in 56% of these workers compared to 7.4% of matched controls from the administrative sector.[73]

NIOSH conducted intramural studies as well. Data from the NOES were analyzed to determine the percentage and number of U.S. workers exposed to five ototoxic solvents by industry sector. Overall, 5 million workers were estimated to be exposed to these solvents.[74] HHEs investigated combined exposures to noise and potential ototoxicants (including solvents, metals, and asphyxiants) within a stock car racing team[75] as well as noise and lead at outdoor firing ranges.[76] At the request of industry representatives, NIOSH conducted an in-depth survey of noise and styrene vapor exposures in fiber-reinforced plastic boat production.[77] To address the similarities in noise-induced and chemical-induced hearing loss (e.g., both tend to be bilateral, symmetric, permanent, and high frequency at onset), NIOSH researchers published a recommended audiological assessment protocol to support distinguishing the effects of noise from the effects of chemicals.[78]

NIOSH work on ototoxic chemicals brought wider attention to the need to expand hearing loss prevention efforts beyond noise. In 1998, the U.S. Army incorporated consideration of exposure to ototoxicants into its hearing conservation program,[79] referencing NIOSH research on ototoxicity in a fact sheet.[80] In 2003, the American Conference of Governmental Industrial Hygienists added a note in the "Noise" section of its *Threshold Limit Values and Biological Exposure Indices (TLVs and BEIs)* stating: "In settings where exposure to toluene, lead, manganese, or n-butyl alcohol occurs, periodic audiograms are advised and should be carefully reviewed."[81] The American College of Occupational and Environmental Medicine, citing NIOSH research, updated its Position Statement on occupational NIHL to recommend consideration of exposure to ototoxicants in evaluating potential cases of OHL.[82] Internationally, Australia, Brazil, and the European Union began addressing ototoxic hazards in worker compensation legislation and worker health and safety standards.[13]

Overlooked and Underserved Populations

Initially, the noise research program at NIOSH (and its predecessor organizations) focused primarily on problems in the manufacturing sector. But as NIOSH entered its third decade, it began to shift its attention to include other groups of workers which presented unique challenges and—in some cases—lacked the regulatory protection of the OSHA noise standard for general industry. Most hearing loss prevention recommendations were designed with stable work environments in mind, in which workers largely performed the same job in the same area under a hierarchical management system that facilitates compliance with safety practices. Translating this approach to other types of employment structures was needed.

The agricultural sector is one example. Farmers are frequently exposed to loud noise from equipment, tools, and even livestock. During busy seasons, their daily exposures can last far longer than 8 hours. Noise exposure can begin at a young age, as many children help on their family's farm.[83] In addition, farmers may be exposed to ototoxic chemicals in pesticides.[84] Exposure to both noise and pesticides can also stretch to nonworkers who live on the farm.[83] Most agricultural workers are not covered by any noise regulation and tend to rely on their own judgments rather than governmental advice.[85] In the early 1990s, hearing loss prevention practices were not widely practiced in this sector.[83]

Noise measurements and hearing thresholds were collected through the Farm Family Health and Hazard Survey, a NIOSH-sponsored, population-based surveillance effort that collected health and hazard data from farm operators and their families in several states.[84,85] Based on these data, NIOSH partnered with individuals and organizations trusted by the agricultural community to promote hearing loss prevention in this population.[83] Together, NIOSH and its collaborators produced two brochures to inform farmers about the hazards of noise and signs of overexposure[86] and to provide guidance on selecting and fitting HPDs.[87] NIOSH received requests for more than 330,000 copies of each brochure.[83]

The construction industry became another focus. Workers in this industry are mobile, often temporary, and have work tasks that frequently change. OSHA regulates noise exposure in this industry under a different standard which stipulates the same exposure limit as for general industry but does not outline specific requirements for managing workers whose exposure exceeds the limit.[88] As a result, very few construction workers during this time period used hearing protection.

An HHE conducted in the mid-1990s at the request of the United Brotherhood of Carpenters found that most carpentry tasks involved exposure to hazardous noise. While this was not surprising, the level of hearing loss sustained by even very young carpenters was unexpected. By the age of 25 years, the average carpenter's hearing thresholds were similar to those of a 50-year-old worker with no noise exposure.[89] Impulse/impact noise was prevalent among carpenters, leading NIOSH researchers to wonder whether this type of noise might be more damaging in less time than earlier field studies had led them to believe. The HHE also found that only 17% of carpenters wore hearing protection at least "most of the time."[90] This prompted a partnership between NIOSH and the United Brotherhood of Carpenters to develop effective hearing loss prevention practices for carpenters and other construction workers.

NIOSH researchers conducted focus groups and key informant interviews to identify attitudes toward hearing loss prevention and barriers to HPD use. They then developed a tailored training program to positively influence attitudes and increase behavioral intentions to use hearing protection.[91] At the end of the project, 82% of participating carpenters indicated that they would use hearing protection (if they had it) every time they were in loud noise.[90]

Workers with hearing loss are a group overlooked by hearing loss prevention regulations. Nearly 50% of the workforce has some degree of hearing impairment, and the proportion is projected to rise with the shifting age demographics of the workforce.[92] Hearing protection differentially affects hearing-impaired workers. While HPDs generally improve signal intelligibility for workers with normal hearing, they often further degrade audibility for workers who have hearing loss, leading to safety risks.

NIOSH researchers collected data from noise-exposed hearing-impaired workers, supervisors of such workers, and managers of hearing loss prevention programs to better understand the effect that hearing loss and noise exposure have on safety, communication, and job performance.[93] Use of hearing aids worn under passive and sound restoration earmuffs was investigated as a method for improving speech intelligibility. A model was developed to assess protected exposure based on the individual worker's noise exposure, hearing aid gain (i.e., amplification), and hearing protector attenuation.[94] In 2005, OSHA issued guidance on hearing conservation practices for workers who have hearing loss, including a recommendation that hearing aids worn under earmuffs be considered "on a case-by-case basis."[95]

Mining Research

Established in 1910 within the Department of the Interior, the U.S. Bureau of Mines (USBM) was charged with protecting the Nation's mining workforce through health and safety research.[96] The USBM was abolished in 1996 and, for a brief time, the USBM Pittsburgh and Spokane Research Centers were part of the U.S. Department of Energy.[97] In late 1996, the centers were transferred to NIOSH and became new divisions within the Institute. At the time, a small hearing loss prevention effort for the mining sector was in place in Pittsburgh. NIOSH expanded on these efforts, investing in facilities, personnel, and training, and established the Hearing Loss Prevention Branch at the Pittsburgh Research Laboratory (PRL). In keeping with its history and Congressional intent, the bulk of research conducted at PRL addresses mining-related issues.[13]

PRL brought with it a large reverberation test chamber, originally constructed in 1983, which had been dormant for several years. With renewed emphasis on hearing loss prevention research, NIOSH upgraded the facility with state-of-the art instrumentation and trained personnel to conduct sound power level testing to evaluate the effectiveness of engineering noise controls.[13] Work completed on continuous mining machines is one example. These machines cut coal from the working face of a mine, collect it, and convey it to the back of the machine to be transported out of the mine. Baseline noise emission testing in the reverberation chamber identified the conveyor as one of the major noise sources. The conveyor is constructed of a metal chain with flight bars that drag the coal to the rear of the machine (see Fig. 6A, B). Noise is generated from metal-to-metal contact between the conveyor and the machine's base as well as metal-to-coal contact as the product drops onto the conveyor. NIOSH engineers developed flight bars with a heavy-duty, highly durable plastic urethane coating, which reduced noise at the operator's position by approximately 7 dBA (Fig. 6C).[98] This noise control has been implemented in industry by a continuous miner manufacturer which produces 80% of the units sold in the

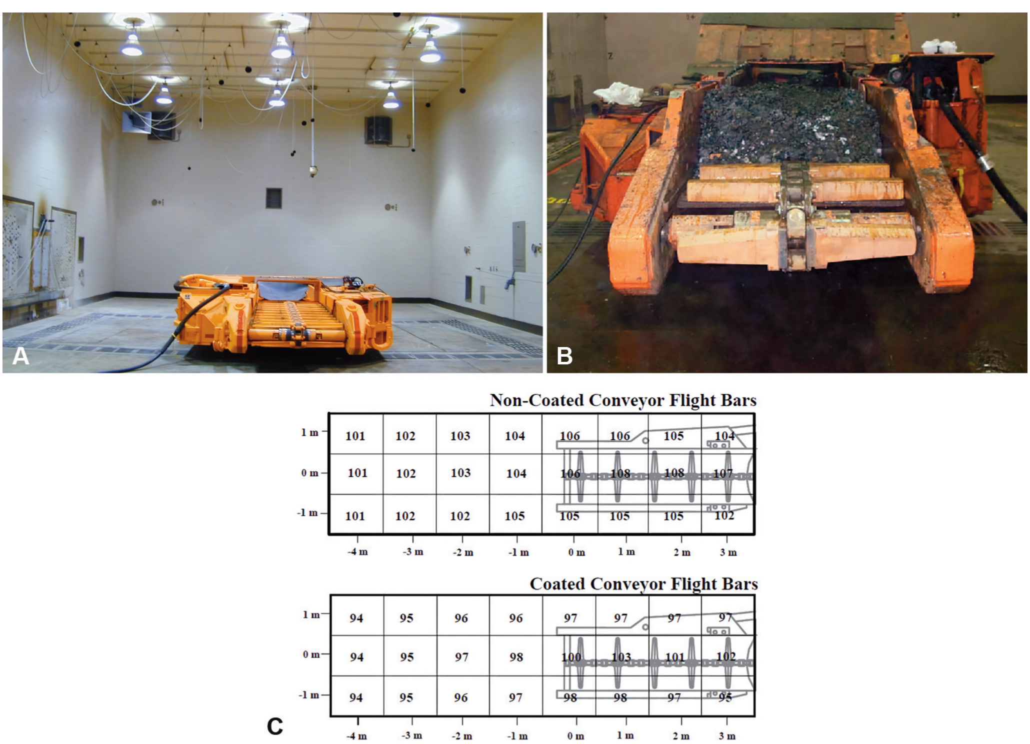

Figure 6 Continuous mining machine in the reverberant test chamber at the Pittsburgh Research Laboratory, empty (**A**) and with a load of synthetic coal used for testing (**B**). Sound levels (dBA) measured in 1-meter intervals over 8 by 3 meter grid surrounding the machine show reductions of 5–7 dBA using the coated flight bars compared to the uncoated bars (**C**).

United States.[13] More information on this noise control effort is published in a related article in this issue of *Seminars in Hearing*.[99]

Reevaluating the Noise Reduction Rating

In the early 1990s, NIOSH began collaborating with the EPA to investigate new test methods for HPDs which could address the discrepancy between laboratory-tested hearing protector attenuation and worker attenuation in the field. In conjunction with related activities of an American National Standards Institute (ANSI) working group, NIOSH participated in a pilot study followed by a full-scale interlaboratory study to investigate testing methods in which subjects fit the HPDs on themselves. Two protocols were tested—an informed-user fit (IUF), in which the tester coached the subject but did not fit the HPD, and a naive subject fit (SF), in which inexperienced subjects fit the HPD based only on the manufacturer's instructions without any input from the experimenter. Attenuation measurements were compared to manufacturers' data obtained according to the EPA experimenter-fit method and to data obtained in various studies of worker attenuation in the field.

Results predictably indicated that both subject-fit protocols resulted in lower attenuation than the EPA protocol. The IUF method resulted in higher attenuation than the SF method for earplugs, but no difference between methods was found for earmuffs. SF data compared favorably with previous field studies of the tested HPDs. Somewhat surprisingly, the study found that the repeatability both within and between subjects was comparable for both the IUF method and the SF method, and that variability across labs was actually lower in the SF data than in the IUF data.[100,101] The working group recommended that hearing protectors be tested using a SF protocol to "estimate achievable real-world attenuation."[100] On the basis of the interlaboratory studies, the ANSI standard for measuring hearing protector attenuation was updated in 1997 to include both the IUF (which it renamed "experimenter-supervised fit") and SF protocols.[102] However, updating the ANSI standard had no effect on EPA regulatory requirements, which were still based on the 1974 ANSI standard. It would be another decade before the EPA proposed updating the regulations governing the NRR.[103]

Revised Noise Criteria Document

A major effort throughout the 1990s was a revision of the 1972 noise criteria document. In the 20+ years since the original recommendations were published, new data and improved scientific methods became available and provided the means to reevaluate earlier decisions.

The cornerstone of the revised criteria document was a reanalysis of the ONHS data which had formed the basis of the 1972 REL.[32,104] The new analysis used contemporary statistical techniques and examined nonlinear models, in contrast to the 1972 analysis which had assumed a linear effect of noise on hearing over time. Based on newer research indicating that hearing ability at 4,000 Hz substantially influences speech understanding, the analysis calculated excess risk of hearing loss among noise-exposed workers using an alternative definition of impairment (i.e., binaural threshold averages at 1,000, 2,000, 3,000, and 4,000 Hz) to those used in 1972 (binaural threshold averages at 500, 1,000, and 2,000 Hz and at 1,000, 2,000, and 3,000 Hz).[104] Based on the results, NIOSH decided to use the alternative definition of impairment, relabeling the term "material hearing impairment" consistent with OSHA terminology. Although the definition of impairment changed, the updated criteria document reaffirmed 85 dBA, calculated as an 8-hour TWA, as the REL.[32]

While the revised criteria document retained the 85 dBA REL, other key recommendations were updated. Rather than the 5-dB exchange rate previously recommended for calculating worker exposure, the 1998 document endorsed a 3-dB exchange rate based on more recent scientific evidence and both national and international consensus. The document also put forward a better criterion for identifying shifts in worker hearing—a 15-dB or more change in threshold at any test frequency confirmed on a consecutive test. Analyses of several hearing shift criteria applied to 15 datasets from industrial audiometric monitoring programs indicated that the criterion originally recommended by NIOSH in 1972 (a 10-dB or more threshold shift at 500, 1,000, 2,000, or 3,000 Hz or a 15-dB or more shift at 4,000 or 6,000 Hz) was too sensitive, whereas the current OSHA criterion (a 10-dB or more change in average threshold across 2,000, 3,000, and 4,000 Hz) was not sensitive enough. The revised criteria document rescinded earlier recommendations regarding age correction. Finally, recognizing the limitations of the NRR but unable to change the regulation, NIOSH proposed a variable de-rating scheme based on hearing protector type (25% for earmuffs, 50% for formable earplugs, 70% for all other earplugs) to better reflect average real-world performance.[32]

Also during this decade, NIOSH commissioned the Institute of Medicine (IOM) National Academy of Sciences to review several of its major research programs, including hearing loss prevention. The review of *Hearing Loss Research at NIOSH* found that NIOSH had made important contributions to reducing occupational noise and hearing loss. The report also made several recommendations to improve the impact of NIOSH research in this area. These included developing a national surveillance program for occupational noise and hearing loss, increasing collaboration with regulatory partners (such as OSHA and the EPA), and extending noise control research to sectors beyond mining.[13] The IOM recommendations influenced noise and hearing loss research at NIOSH over the next decade and beyond.

2000s—PROMOTING BEST PRACTICES AND EXPANDING COMMUNICATION

The turn of the millennium brought new challenges and new opportunities to NIOSH. Several Institute-wide initiatives were launched over the course of the decade that emphasized promoting best practices and aligned well with ongoing hearing loss prevention efforts. Among them was the Steps to a Healthier U.S. Workforce Initiative, which grew into the NIOSH Total Worker Health (TWH) program.[70] Even before NIOSH was created, the federal Division of Occupational Health had recognized that "the worker is, and reacts, as a whole man, not as an isolated system responding to a single stimulus." Therefore, an integrated approach to workplace health and safety is required.[21] The TWH program puts this axiom into action by encouraging employers to establish comprehensive policies and practices that address both workplace and personal health risks as a more effective way of promoting health and safety on- and off-the-job. This principle translates perfectly to a total hearing health approach to hearing loss prevention. Expanding occupational hearing conservation programs beyond the workplace and integrating hearing loss prevention activities into other areas of professional practice and community outreach is the best method for preserving hearing health.[105]

Steps toward Addressing Surveillance

Surveillance is the ongoing, systematic collection, analysis, interpretation, and dissemination of health-related information for the purpose of preventing or controlling disease or injury.[16] OHL surveillance includes collecting worker hearing data, exposure data, and related information to estimate how many workers are exposed and how many workers have hearing loss or related health outcomes. Estimates of incidence, prevalence, and risk are examined by industry and occupation and monitored for trends over time to guide prevention and research efforts and evaluate the success or failure of interventions. Surveillance is vital to OHL prevention, as program recommendations from the 1988 *Proposed National Strategy*[54] to the 2006 IOM review[13] had emphasized.

However, national surveillance programs are expensive, and the hearing loss research program lacked resources to establish an ongoing surveillance system. NIOSH researchers therefore worked to address the data gap through existing survey systems. Beginning in the late 1990s and continuing through the present, NIOSH has collaborated with the National Institute on Deafness and Other Communication Disorders, part of the National Institutes of Health, to provide support for hearing content in two prominent CDC population surveys—the National Health and Nutrition Examination Survey (NHANES) and the National Health Interview Survey (NHIS). Both surveys provide nationally representative data on the noninstitutionalized U.S. population.

NHANES collects data through questionnaires and exams. Using mobile examination centers which travel across the country, NHANES conducts pure-tone air conduction audiometry on various age groups over time, and collects related self-reported data on hearing ability, noise exposure, tinnitus, and HPD use. Since 1997, NIOSH researchers have managed the NHANES audiometric data collection process, contributed to the development of its hearing-related survey content, and completed surveillance studies examining survey results.

For example, NIOSH analyzed data from NHANES 1999–2004 to determine a more current estimate of the number of U.S. workers exposed to noise, as no new exposure data had been collected since the NOES in the early 1980s. The analysis indicated that 17% (22 million) workers were exposed to noise on-the-job. NIOSH also examined self-reported HPD use and found 34% of workers reported never using hearing protection when exposed to noise at work. A deeper look at HPD use by industry showed an inverse relationship between the prevalence of noise in an industry and failure to use HPDs when exposed to noise (see Fig. 7). Workers in industries in which high noise levels are common are more likely to use hearing protection than workers in industries in which high noise levels are rare.[106] This finding supports the earlier efforts by NIOSH researchers to focus hearing prevention efforts on underserved industries.

NIOSH researchers also contributed to the development of hearing-related survey content in the NHIS and funded NHIS occupational

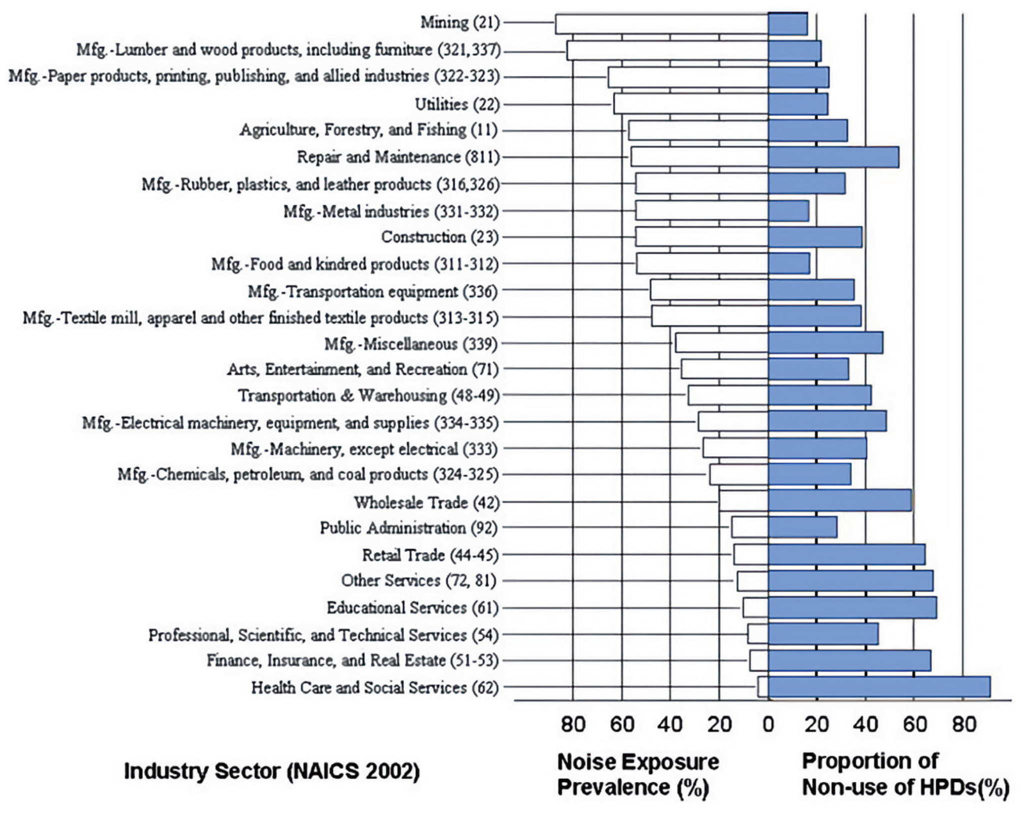

Figure 7 Prevalence of self-reported occupational noise exposure compared to prevalence of never using hearing protection by industry among currently working U.S. adults aged 16 years and older. Data from NHANES 1999–2004. (Reprinted with permission from Tak et al[106]; Fig. 1.)

supplements. This survey collects data solely through a personal interview; so, data are based entirely on self-report. However, the sample is much larger than NHANES, allowing for examination by industry and occupation using a single year of data.

An additional step toward national surveillance data for OHL occurred during this decade. OSHA issued an updated form for reporting occupational illnesses and injuries, adding a dedicated column for hearing loss.[107] Previously, hearing shifts had been grouped together with other repetitive trauma disorders and could not be tracked independently. The Bureau of Labor Statistics (BLS) annual *Survey of Occupational Injuries and Illnesses* publishes incidence statistics each year from data reported on the OSHA form, allowing new cases of hearing shifts to be tracked over time. However, the degree of hearing shift that must occur before it is recordable on the log and disincentives to employer reporting have led some to estimate that the BLS data may underestimate rates of hearing loss by as much as an order of magnitude.[108] Nonetheless, these data enabled NIOSH to place an objective to reduce new cases of noise-induced hearing threshold shifts in Healthy People 2020[109] and Healthy People 2030,[110] keeping OHL on the nation's public health agenda.

More Work on Hearing Protector Labeling

In 2003, the EPA hosted a workshop in Washington, DC, organized and facilitated by NIOSH, to identify the changes needed to address the shortcomings in the hearing protector labeling regulation. Participants included experts from government, academia, manufacturing, and testing laboratories. The workshop discussed two overarching issues: overestimation of worker attenuation with the experimenter-fit testing protocol and lack of test procedures for labeling nonconventional HPDs (such as nonlinear protectors which provide different levels of protection in different levels of noise).[111]

To address the first issue, EPA asked NIOSH to organize a second interlaboratory study comparing experimenter-supervised fit and naive subject fit attenuations, due to the unexpected finding in the first interlaboratory study of lower variability in the subject fit method.[111] Through an interagency agreement, EPA funded NIOSH to conduct this study across six testing labs in the United States and Brazil. Unlike the first interlaboratory study, the new study reported smaller standard deviations within and between subjects when using an experimenter-supervised fit. However, the new study confirmed the original finding of lower between-lab variability when using a naive subject fit.[112] As a result of the study, the ANSI hearing protector attenuation standard was revised again in 2008 to provide more specific protocols for both procedures.[113] After much debate regarding which procedure was more appropriate for hearing protector labeling,[112] the EPA proposed revising the HPD labeling regulation to require measuring attenuation using an experimenter-supervised fit.[103]

In addition to evaluating more predictive methods for measuring attenuation, NIOSH collaborated on developing more useful single-number estimates of a worker's protected exposure level under an HPD. The NRR had been designed to be subtracted from a worker's C-weighted noise exposure. However, nearly all workplace noise in the United States is measured on an A-weighted scale. Data from the NIOSH/EPA interlaboratory study were used to develop the Noise Reduction Statistic for use with A-weighted noise measurements (NRS_A) which could be directly subtracted from a worker's exposure level without the adjustment required when using the NRR.[114] The NRS_A was incorporated into a new ANSI standard.[115]

The second issue raised at the 2003 NIOSH/EPA workshop was the need for appropriate methods for labeling performance of nonlinear (level-dependent) HPDs. These devices use passive design characteristics or active electronics to vary attenuation based on the sound level in the environment. When the noise levels are quiet, the HPD allows sound to pass through the protector. When noise levels become hazardous, the HPD attenuation increases. Because low level sounds pass through the protector, REAT testing (which uses low level test signals to measure a person's threshold with and without the protector in place) results

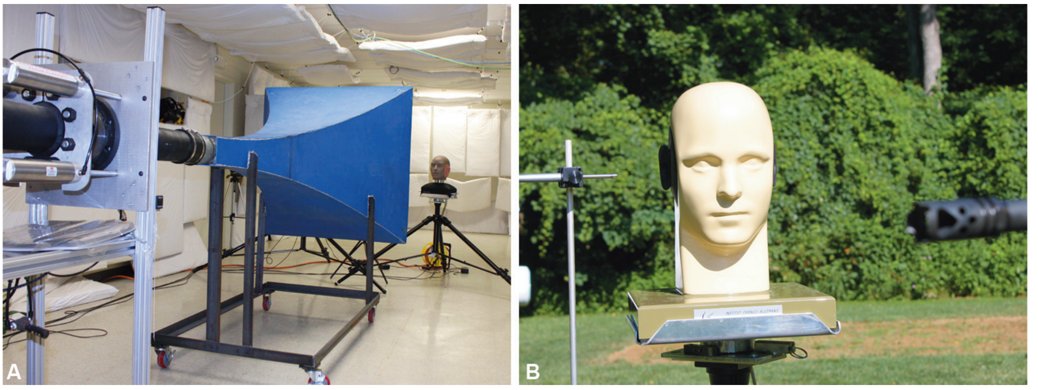

Figure 8 Using auditory mannequins to study impulsive noise in the lab (A) and in the field (B).

in NRRs which are effectively zero. In addition, HPDs which utilize electronics (such as active noise cancellation [ANC], which measures noise under the HPD and generates a signal opposite in phase to effectively cancel the sound transmitted to the ear) can produce noise through the speakers in the HPD and interfere with the REAT procedure.

To address these issues, NIOSH worked with the same ANSI working group to develop appropriate standards for measuring the performance of the nonlinear aspects of these types of HPDs.[111,116,117] For HPDs which use design characteristics or electronics other than ANC, procedures were developed for measuring insertion loss (the difference in sound level in the ear canal with and without the protector in place) on an acoustic text fixture (i.e., artificial head; see Fig. 8). High-level impulsive test signals are generated through gunshots (Fig. 8A) or an acoustic shock tube (Fig. 8B). A new ANSI standard defined an attenuation metric known as impulse peak insertion loss (IPIL) to describe the performance of these protectors under high noise conditions.[117] Procedures for measuring the noise reduction added to a protector through ANC technology were also developed. Results can be added to the REAT attenuation to describe the total attenuation for ANC devices.[117]

This work formed the basis of a proposed revision to the EPA hearing protector labeling regulation. Conventional hearing protectors would be tested using the experimenter-supervised fit procedure and REAT measurements. The NRR metric would be replaced by the NRS_A. Nonlinear devices would be tested in the same way but also have additional testing to describe their attenuation with ANC circuitry activated or their IPIL in high-level noise, as appropriate. The EPA proposed the new rule in August 2009[103] and held a public comment hearing in November 2009. However, the changes were never promulgated. Although new ANSI standards developed through these efforts provide guidance for better characterizing HPD performance, the NRR and HPD labeling requirements remain today as originally published in 1979.

Expanding Mining Research and Outreach

NIOSH broadened its hearing loss prevention efforts during this decade by developing a set of worker empowerment interventions. Though developed for the mining sector, these tools have utility for other persons exposed to noise on-the-job (and even off-the-job). For example, the NIOSH Hearing Loss Simulator is an online tool for demonstrating the effects of noise exposure on hearing without experiencing an actual NIHL. Users can enter sample audiograms into the software or choose from preprogrammed audiograms based on age and noise exposure history. Then they can listen to how a variety of speech, music, and machinery sounds would be heard with that type of hearing loss.[118] NIOSH developed several fact sheets for worker education and training as well.

These included an instruction sheet and video for properly using foam earplugs[119] and a fact sheet detailing what an audiogram is, why you should get regular audiograms, and how to understand the results.[120]

As time went on, NIOSH assessed barriers to effective hearing loss prevention programs and created new educational aids to help overcome them. For example, the "CAP the Noise" campaign promoted three methods for protecting against the effects of hazardous noise—Control (engineering controls), Avoid (administrative controls), and Protect (hearing protection). The campaign distributed flyers and hardhat stickers to remind miners that NIHL is preventable.[121] The "Now Hear This!" infographic is another example. It illustrates the "dos and don'ts" for protecting against the effects of loud noise.[122] As with many other materials developed by the NIOSH mining team, "CAP the Noise" and "Now Hear This!" transfer readily across industries. These tools are all still current and available.

From 2000 to 2007, NIOSH conducted a series of cross-sectional surveys to determine noise exposure patterns, noise sources, and worker exposure levels across various mining commodities. Color contour mapping techniques were used to illustrate noise levels in the vicinity of mining equipment. The project resulted in a large set of noise data covering a wide range of mining equipment and occupations in coal, metal/nonmetal, and stone, sand, and gravel mines.[123–125] Survey data were used to prioritize research efforts, particularly in the area of noise control. NIOSH continued its mining engineering control development research, addressing a variety of heavy mining equipment to reduce noise emission and worker exposure. Successful controls were developed for surface drill rigs,[126] coal mining roof bolting machines,[127] horizontal vibrating screens,[128] and jackleg drills.[129]

In addition to developing specific noise control solutions for large equipment, NIOSH produced a nontechnical noise control guidance document for mine operators, safety personnel, mechanics, and others who do not have a background in acoustical engineering. The guidance document provides information on some simple approaches to reducing sound levels and methods for evaluating their effect.[130] Like many of the worker empowerment tools described earlier, the principles and examples in the noise control guidance document could be applied to noisy industries outside of the mining sector as well.

Effective Worker Training

The OSHA noise standard for general industry requires annual training for noise-exposed workers,[31] and the NIOSH *Practical Guide* emphasizes that such training should be "tailored to the company's particular hearing loss prevention needs."[36] However, experiences with the construction industry highlighted just how important it is to customize training, education, and motivational strategies for the specific audience. NIOSH therefore turned to the science of health promotion and health communication to study effective training methods, particularly with regard to effective use of hearing protection.

Continuing their partnership with the United Brother of Carpenters, NIOSH applied health promotion theory to the data they had collected from these workers on attitudes and barriers to hearing protector use. For example, the Health Belief Model maintains that effective training must convince participants that a problem exists, that it pertains to them, that it is important for them, and they are able to do something about it.[131] Generic hearing conservation training that simply states that "noise causes hearing loss" only addresses the first concept (i.e., that a problem exists). Training that stops there will be ineffective. NIOSH developed training materials that incorporated the remaining concepts by addressing attitudes and barriers toward the use of hearing protection to prevent hearing loss and promoting a sense of self-efficacy.[90,91]

NIOSH also applied health communication theory on message framing to improve training content. Health communication research indicates that messages focusing on "gains" (e.g., preserving hearing) are more effective for promoting prevention behaviors (e.g., wearing hearing protection), whereas messages focusing on "loss" (e.g., losing hearing) are more effective in promoting detection behaviors (e.g., getting an annual audiogram). NIOSH used this information to appropriately orient content in its training materials.[91]

Evaluating the effect of training modality was another area of research. From its research on the field attenuation of hearing protectors, NIOSH understood that fitting hearing protectors solely on the basis of the manufacturer-supplied instructions resulted in poor attenuation. Therefore, NIOSH conducted several studies to determine the relative effectiveness of video instruction, small group instruction, and one-on-one instruction. In the first study, 100 inexperienced HPD users fit the devices on themselves using only the manufacturer-printed instructions and noise reduction was measured. Participants were then randomly assigned to receive 20 minutes of instruction from the experimenter either individually or in groups of four to six. Results indicated that experimenter instruction resulted in an increase of at least 8 dB in overall sound reduction compared to the manufacturer's instructions alone. The effect was similar for both individual and small group instruction and for both preformed and formable earplugs.[132] NIOSH conducted a second study using a NIOSH-designed training video with device-specific instructions as one of the training modalities instead of small group instruction. Results indicated no difference in the participants' ability to fit the HPDs between the written and video instructions, but increases of 5 to 10 dB in overall attenuation with the individual training.[133] These studies, as well as work which NIOSH has continued to do in this area, indicate that in-person instruction is essential for training workers to wear hearing protection properly.[134]

Safe-In-Sound Awards

One of the recommendations which came out of the 2006 IOM review of the NIOSH Hearing Loss Prevention Research Program was to evaluate the effectiveness of hearing loss prevention measures using—insofar as possible—actual (rather than planned) workplace health behaviors.[13] NIOSH created the Safe-In-Sound Excellence in Hearing Loss Prevention Award program as one means of addressing this recommendation.[135] The award recognizes innovative and successful real-world OHL prevention strategies. These evidence-based strategies are disseminated to the hearing conservation community to provide ideas for others to potentially implement in their own programs. In addition, NIOSH researchers study these proven approaches to identify underlying characteristics that should be leveraged to effectively reduce noise exposure and hearing shifts, and then use this information to guide future research and recommendations.[135,136]

NIOSH partnered with the National Hearing Conservation Association (NHCA) to create the award. The first set of winners were recognized at the NHCA conference in 2009, and subsequent awards have been presented during the conference each year since.[135–137] Award recipients have included company hearing loss prevention programs, hearing conservation service providers, manufacturers of innovative products, advocacy organizations, and educational programs. In 2018, the Council for Accreditation in Occupational Hearing Conservation joined the Safe-In-Sound award partnership.[135]

NIOSH has analyzed the winning strategies to identify underlying characteristics that support successful hearing loss prevention efforts. These include underlying organizational values (e.g., emphasizing integrity, innovation, and trust in employee judgments), supportive work environments (e.g., assigning clear roles, requiring accountability at all levels, and recognizing that time is necessary to overcome barriers), and dedicated program personnel (e.g., being passionate about hearing loss prevention, leading by example, and communicating frequently across all levels). Aspects of successful hearing loss prevention programs include prioritization of noise control, individualized worker training, and extension of hearing conservation efforts beyond the workplace. A surprising number of innovative noise control projects—some requiring little or no cost—have been highlights of the award program.[136]

New Communication Tools

Communication has always been an essential part of the NIOSH mission. Early in its history, NIOSH focused on publishing criteria documents, technical reports, and peer-reviewed journal articles. Over time, NIOSH began to expand its communication toolkit to reach the full range of occupational safety and health constituents, ranging from academia to workers themselves. The growth of the internet and launch of the NIOSH website in 1996 expanded opportunities to engage audiences. Beginning in the 2000s, NIOSH improved both the scope and timeliness of its communications via social media with its various audiences.

NIOSH launched its Science Blog and posted its first YouTube video in 2007, joining Facebook in 2008, establishing a Twitter account in 2009, and moving into Instagram in 2014.[138,139] NIOSH hearing loss prevention staff have leveraged these new tools extensively. The first hearing-related blog was published in 2008, and over 40 others have been published since covering topics from cicadas to NASCAR, from measuring impulse/impact noise to choosing the best HPD.[140] A dedicated Twitter account for NIOSH noise research—@NIOSHNoise—was created in 2010 and currently has nearly 6,000 followers. The noise group also posts content on the main NIOSH Facebook and Instagram channels.

Another rapidly growing communication resource is Wikipedia, which launched in 2001. Wikipedia is an open-access, user-edited encyclopedia website that has a potentially unlimited number of topic areas. It has become a popular source of health information for both professionals and the general public. To ensure that Wikipedia articles offer the most up-to-date, evidence-based information, NIOSH has engaged in writing and reviewing Wikipedia content.[141] NIOSH noise researchers and communication staff members, in collaboration with the NIOSH Wikipedian-in-Residence, have worked on creating or contributing to many articles related to OHL prevention. NIOSH has led efforts to add and expand hearing-related content on Wikipedia, such as for World Hearing Day in 2019 and the Year of Sound in 2020. The latter resulted in the addition of 235,000 words and over 900 references to 1,000 existing and 80 new Wikipedia articles, which received more than 131 million views during the tracking period.[142] NIOSH has also spearheaded incorporating Wikipedia editing into university courses in audiology, epidemiology, and occupational health.[143,144]

2010s—IMPROVING SURVEILLANCE AND LEVERAGING NEW TOOLS

With technology advancing rapidly, NIOSH entered the 2010s with an array of new and faster tools at its disposal. The advent of big data and processing tools such as machine learning and artificial intelligence makes actionable evidence available in a fraction of the time and cost previously required. Crowdsourcing facilitates gathering information or ideas from large numbers of people in a short period of time to answer a question or work on a solution.[145] Direct reading instruments and "smart" sensors enable real-time data collection and analysis that can be translated into near-immediate worker-level warnings to reduce exposures and improve safety.[146] Data visualization techniques put tailored information at the fingertips of the end user with just a few clicks of a mouse, prompting certain NIOSH tools, such as the Worker Health Chartbook,[147] not only to move online but to become interactive.

NIOSH established new centers and programs which leveraged these technological advances throughout the decade. The Prevention through Design (PtD) program published its *Plan for the National Initiative* in 2010.[148] This initiative promotes elimination of potential hazards during the design process as the most effective means of preventing worker exposure. In 2014, NIOSH established a Center for Direct Reading and Sensor Technologies to coordinate research and develop recommendations on how to leverage the potential of these new tools, while managing the accompanying challenges of privacy and trust.[149]

Also in this decade, NIOSH established its National Center for Productive Aging and Work to address the unique needs of older workers who make up an increasing segment of the workforce,[150] and the Safe • Skilled • Ready Workforce Program to focus on young workers.[151] The latter has produced a set of state-specific occupational safety and health curricula that include an activity focusing on hearing loss prevention.[152] The NIOSH Center for Workers' Compensation Studies (CWCS) was launched in 2013 and utilizes various workers' compensation data sets to monitor trends in job-related conditions, evaluate the effectiveness of interventions, estimate the economic impact of occupational illnesses and injuries, and other research activities.[153] Staff from CWCS and the Hearing Loss Prevention Research Program coauthored an analysis of data on workers' compensation for hearing loss which is published in this issue of *Seminars in Hearing*.[154]

Occupational Hearing Loss Surveillance Program

Surveillance using CDC population surveys—NHANES and NHIS—continued into the 2010s and beyond. However, a more comprehensive system for OHL surveillance that includes longitudinal results of pure-tone audiometric testing, from which clinical determinations of hearing loss can be made for large numbers of noise-exposed workers, was needed.[13,54] This is necessary to identify high-risk worker populations, evaluate the effectiveness of intervention strategies, and monitor progress in prevention. The NIOSH OHL Surveillance Project (now Program) was initiated in 2009 to fill this critical gap.[155]

The program leveraged data already being collected through audiometric monitoring in OHL prevention programs for regulatory compliance. Partnerships were established with 24 worker hearing testing providers to develop the single largest repository of U.S. private sector worker audiometric data for surveillance and research, with more than 12 million records of varying quality collected as of 2021. NIOSH also developed a key partnership with the United States Air Force to collect noise-exposed military worker audiometric data and associated noise and ototoxic chemical exposure information. Approximately 5.5 million audiometric records were collected along with exposure data.

Through the Program, NIOSH published the first estimates of hearing loss prevalence and risk among noise-exposed U.S. workers by industry using audiograms for over 1 million workers.[155] This study identified the highest-risk sectors for hearing loss, including mining and construction, but also revealed that there were noise-exposed workers at increased risk in perceived "low-risk" industry subsectors, such as real estate.[155] In 2016, OSHA scheduled a request for information preceding a rulemaking to update the construction noise exposure regulation, motivated by two articles, one of which was this study that highlighted the high prevalence and adjusted risk for hearing loss among noise-exposed workers in the construction sector.[156]

Another NIOSH surveillance study compared OSHA and NIOSH hearing shift criteria.[157] This study demonstrated that a third of workers who had significant hearing shifts and needed intervention to prevent additional hearing loss were being missed by hearing conservation programs when age correction was applied to hearing loss assessments. This study also found that, in the absence of age correction, using the OSHA criterion for a significant loss in hearing (10-dB or more change in average threshold across 2,000, 3,000, and 4,000 Hz) missed an additional third of workers who needed intervention when compared with using the recommended NIOSH criterion (confirmed 15-dB change at any frequency). The National Institute of Standards and Technology (NIST) updated their hearing conservation program based primarily on this analysis. NIST now no longer uses age correction.[158]

Also using the program audiometric dataset, NIOSH published 30-year trends in hearing loss prevalence among noise-exposed workers by industry sector (1981–2010), and 25-year trends in incidence and adjusted risk by industry sector (1986–2010). No such long-term trend results were previously available to evaluate the success or failure of U.S. hearing loss prevention strategies.[159] This study found that the overall adjusted risk of hearing loss for noise-exposed workers in all industries combined decreased by 46% over 25 years, indicating that there had been progress in prevention among high-risk workers. While all sectors had risk reduction, some sectors

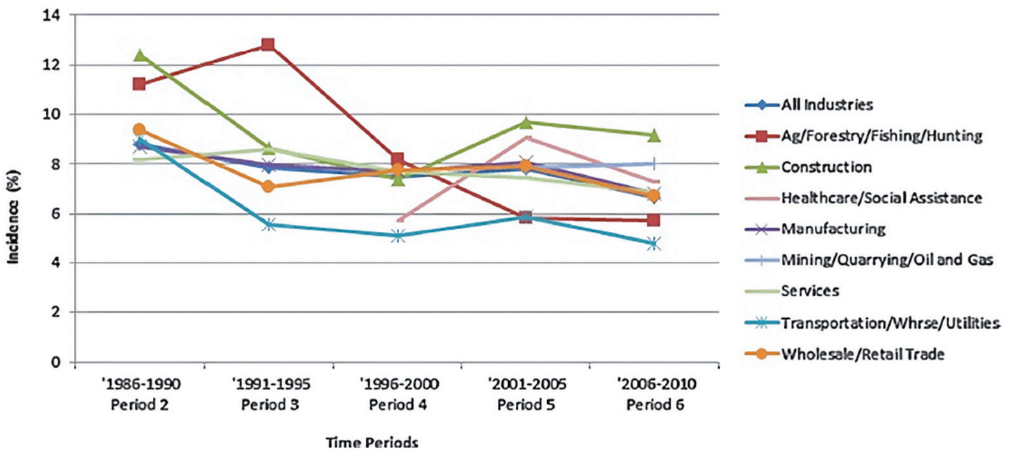

Figure 9 Trends in incidence of material hearing impairment over time by industry sector. Period 1 (1981–1985) is the reference period from which new cases of hearing loss are counted in Period 2. Data on 560,320 workers from the OHL Surveillance Program, 1981–2010. (Reprinted with permission from Masterson et al[159]; Fig. 2).

had less than others, and the results depicted the sharp contrast in the patterns of prevalence and incidence among industries over time (see Fig. 9).[159]

NIOSH has also used data from the OHL Surveillance Program to examine U.S. hearing loss prevalence and risk among noise-exposed workers in specific industry sectors, including services[160]; health care and social assistance[161]; agriculture, forestry, fishing, and hunting[162]; mining[163]; and oil and gas extraction (OGE).[163] These analyses provided, for the first time, prevalence and risk estimates for most subsectors in each industry, highlighting the high prevalence of hearing loss in certain subsectors which need targeted interventions. The raised awareness of the risk of hearing loss among OGE workers and lack of surveillance data in certain OGE subsectors prompted action in this sector. Based on this article, the Association of Energy Service Companies (AESC) requested that hearing loss be included as one of the priorities for action in their agreement with NIOSH (Kyla D. Retzer, e-mail communication, October 2019). This was a significant step in the recognition of noise as a hazard in the OGE sector, which is exempted from current noise exposure regulations.

The analyses of population survey data described earlier continued through the 2010s. In 2016, NIOSH used 2007 NHIS survey data to publish the first study of prevalence and adjusted risk for hearing difficulty, tinnitus, and their co-occurrence among workers by industry, occupation, severity, and noise exposure status.[164] Study results indicated that among U.S. workers never exposed to occupational noise, 7% reported hearing difficulty, 5% reported tinnitus, and 2% reported both conditions. However, among those workers who had ever been exposed to occupational noise, the prevalence was 23, 15, and 9%, for hearing difficulty, tinnitus, or both conditions, respectively.[164] This article quantified the significant elevation in the prevalence of hearing loss and tinnitus among workers who are exposed to occupational noise as compared with nonexposed workers and raised awareness of tinnitus as a work-related condition.

Using 2014 NHIS data, NIOSH examined occupational noise exposure, self-reported hearing difficulty, and cardiovascular conditions by industry and occupation. Results indicated an association between occupational noise exposure and hypertension and elevated cholesterol.[8] This article estimated that 58% of worker hearing losses were caused by occupational noise and that hearing and associated quality of life could be preserved for 5.3 million workers if U.S. civilian workplace noise was reduced to a safe level. It also estimated that 14% of potential cases of worker hypertension and 9% of cases of elevated cholesterol could be prevented, if a causal link exists between noise and these conditions.[8] These numbers highlight that noise is associated with outcomes in addition to hearing loss and are important for prioritizing research and allocating public health resources.

NIOSH Sound Level Meter App

The rapid growth in mobile phone technology and expanding penetration of "smart" devices in the cellular phone market corresponded in time with NIOSH initiatives on direct-reading methodologies and wearable sensors. Sound level meters (SLMs) and dosimeters have functioned as direct-reading instruments for decades. However, microphones built into smartphones coupled with the processing capabilities of the phones' integrated circuitry, which far surpasses that of traditional SLMs, effectively made it possible to put sound measurement devices into millions of hands. As dozens of noise measurement smartphone applications (apps) became available in the early part of the decade, NIOSH began to investigate their accuracy and suitability for assessing noise levels in the workplace.[165,166]

In 2014, NIOSH reviewed nearly 200 sound measurement apps developed for the iOS and Android platforms. Fourteen apps were selected based on criteria important to measuring noise for OSH purposes (e.g., calibration function, A-weighted measurement scale, ability to calculate time-weighted averages). They were tested against a Type 1 SLM in a reverberant acoustic chamber (Fig. 10A). Results showed substantial variability in measurement accuracy both across apps and within apps across devices (Fig. 10B). However, average A-weighted measurements from three of the apps met the accuracy requirements of ANSI S1.4-1983 (R2007) for Type 2 sound measurement devices, indicating that they could potentially be used in hearing loss prevention programs.[166]

The 2014 study noted the inaccuracies in sound measurements made by smartphone apps stemmed largely from limitations inherent to the phones' internal microphones.[166] Therefore, NIOSH repeated the study in 2016 using four iOS apps from the original study that allowed measurement from an external microphone attached through the headset jack input. Measurements were made using two different omnidirectional, electret-condenser microphones selected on the basis of their wide availability and ability to be calibrated using an off-the-shelf acoustical calibrator and adapter. Measurements made using the external microphone showed no significant differences from the reference measurement, across apps, or across devices.[167]

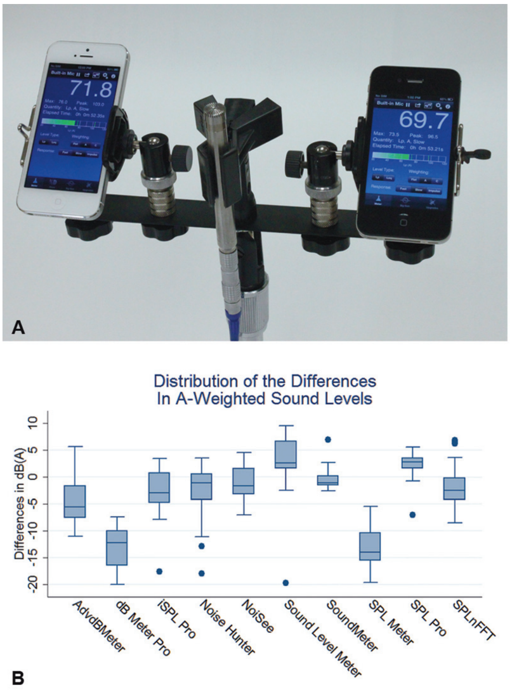

Figure 10 Set-up for testing the accuracy of sound measurement apps in the NIOSH laboratory (**A**). Two smartphones running sound measurement applications (apps) are on the left and right. A half-inch Type 1 random incidence microphone in the center is connected to a measurement system outside the chamber. Results (**B**) indicated variability across different apps and within the same app run across different devices.

Despite the accuracy of some sound measurement apps, particularly when used in conjunction with an external microphone, NIOSH researchers realized that most of the apps lacked some functions which are important when measuring occupational noise. Therefore, NIOSH partnered with EA LAB to develop an app designed for OHL prevention. The NIOSH Sound Level Meter App was released in 2017.[168] The app meets the ± 2 dB accuracy criterion for Type 2 SLMs. It offers all of the functions necessary for measuring occupational noise—instantaneous sound levels using A, C, or Z-weighted scales; necessary metrics (e.g., A-weighted equivalent sound level [L_{Aeq}], C-weighted peak SPL [L_{Cpeak}], time-weighted average [TWA], dose); a calibration function; and user-controlled settings. The app can interface with a phone's global positioning system (GPS) function to record the measurement location. Results can be saved and shared using the phone's communication functions. The app also includes educational tools covering basic aspects of OHL prevention.[168] Initially, the app was developed only for iOS platforms, due to the consistency in their hardware, software, and audio capabilities across devices. Future efforts will work toward developing an Android version; these devices are much more variable, making it difficult to assure accuracy and functionality for all device models.

Interest in using apps for OHL prevention runs very high. The blog summarizing the results of the 2014 study of noise measurement apps remains the most visited NIOSH Science Blog of all time (Garret Burnett, e-mail communication, August 2022). The NIOSH SLM app has been downloaded more than 1.5 million times (Chucri Kardous, e-mail communication, August 2022). Apps can be convenient and accessible tools for checking noise levels, raising awareness of hearing hazards, and informing decisions about protective behaviors. They can also expand research opportunities for collecting noise data, targeting intervention efforts, and evaluating progress. This area of research is likely to grow quickly in the coming years.

Developments Regarding Impulse/ Impact Noise

NIOSH and other organizations and researchers continued to investigate the relationship between impulse/impact noise exposures and hearing damage in an effort to develop an exposure metric that would establish damage-risk criteria and guide recommendations regarding exposure limits. Total sound energy alone had been shown to be an inadequate measure of hearing risk. In addition to kurtosis, other proposed metrics included peak sound pressure, rise time, initial impulse duration (A-duration), reverberation (B-duration), number and timing of impulses, spectral content, and number of impulses in an entire exposure. None were completely satisfactory.[169]

U.S. Army researchers developed a mathematical model of the peripheral auditory system known as the Auditory Hazard Assessment Algorithm for Humans (AHAAH) model to predict hearing damage from intense high-level sounds. The model calculated exposure in terms of auditory hazard units (AHUs). Controversially, the AHAAH model assumed the protective effect of an activated acoustic reflex in calculating AHUs.[170] NIOSH researchers participated in an American Institute of Biological Science review of this model, which was favorable but did not critically compare with other potential damage-risk criteria. NIOSH also participated in an ANSI Subcommittee S3 for Bioacoustics, Working Group 62, which considered adopting the AHAAH model as part of a new standard on "Estimation of the Hazards Posed by Exposure to Impulse Noise." However, the new standard failed to obtain consensus and was dropped. Following these efforts, NIOSH became more involved in working with the military on damage-risk criteria for impulse noise exposures.

As part of this work, the Office of Naval Research funded NIOSH to develop a protocol to investigate the pervasiveness of the acoustic reflex to evaluate assumptions regarding it in the AHAAH model. Acoustic reflex data collected in NHANES from more than 15,000 persons were analyzed to estimate the prevalence of the acoustic reflex. Among normal hearing individuals, the prevalence of acoustic reflexes was approximately 85%, but prevalence decreased markedly with age and mild-to-moderate hearing loss.[171] Prevalence was lower, even among normally hearing individuals, with elicitation by an impulse stimulus, tone burst, or noise burst.[172] A separate set of studies investigated whether the acoustic reflex could be conditioned to activate in anticipation of a high noise exposure. Results indicated that it could not.[173] These studies argued against assuming an activated reflex in the AHAAH model, as the reflex was not pervasive and could not be conditioned. As a result, NIOSH is continuing to work with staff from the military and academic laboratories to evaluate other potential damage-risk criteria for assessing the risk from impulse/impact noise.

Additional developments occurred in the area of instrumentation for measuring impulse/impact noise. Several HHEs brought renewed attention to problems in accurately measuring impulse/impact noise exposures.[174–176] Many of the limitations which NIOSH had highlighted in the 1980s still existed in commercially available dosimeters. Microphones had insufficient high-frequency response and dosimeters had insufficient dynamic range to fully capture the peak exposure. This resulted in "clipped" measurements which underestimate exposure. Furthermore, the metrics reported by dosimeters are relevant to continuous noise, but parameters useful in characterizing impulse/impact noise exposures are not provided.[169] To provide a means for accurately measuring occupational impulse/impact noise, the NIOSH Impulsive-noise Measurement System (NIMS) was developed and commercialized.[177] NIMS can correctly capture impulses up to 186 dB (or higher if coupled with a very low sensitivity polarized microphone). Measurements can be made in real time and a number of relevant impulse/impact noise metrics (e.g., peak level, B-duration, spectrum, temporal spacing, number of impulses, kurtosis, and L_{eq}) can be obtained immediately. NIMS calculates risk based on several damage-risk criteria, including the L_{Aeq8hr} and AHAAH. It also stores waveforms for post hoc analyses.[169]

A suitable dataset for developing RELs for impulse/impact noise is needed. NIMS may change that by providing the necessary instrumentation to accurately characterize exposures. Noise data characterized by NIMS or other systems built with the same capabilities should move the research forward to eventual establishment of reliable exposure limits for impulse/impact noise.[169]

Hearing Protector Fit-Testing

The unsuccessful attempt to update the EPA hearing protector labeling regulation in the 2000s left the NRR in place, along with various de-rating approaches to account for its shortcomings. However, the reality is that any hearing protector attenuation rating will always be a statistical estimate that may or may not reflect the actual sound reduction that a particular worker receives from the device. The real solution to the problem is to measure attenuation on each individual worker.[32] This is accomplished through hearing protector fit testing.

The concept of HPD fit testing has been around for some time. As noted earlier, NIOSH commissioned a hearing protector fit-test system to conduct its studies comparing the NRR to real-world attenuation in the 1970s. However, the system required large equipment unsuited to implementation in company hearing loss prevention programs. The advent of the personal computer enabled the development of fit-testing systems that were more portable.

In the 1990s, Michael and Associates introduced a smaller version of the fit-test system Paul Michael developed for NIOSH in the 1970s. It required only a personal computer

Figure 11 A NIOSH researcher conducting hearing protector fit-testing using a Real Ear Attenuation at Threshold (REAT)-based system at a construction job site. The worker listens to test signals through a set of large-volume headphones while the tester establishes hearing thresholds with and without the earplugs in place.

with a sound card, attenuator box, response switch, and large-volume headphones. This system, known as Fit Check, was used by a number of companies, by the U.S. Army, and by researchers at NIOSH. As personal computers advanced, HPD fit testing could be accomplished with just a laptop or mobile device that could drive headphones and provide an interface (see Fig. 11). By the end of the 2000s, several fit-testing systems had become commercially available.

Contemporary hearing protector fit-check systems have improved the feasibility of evaluating noise reduction on individual workers. Nearly all fit-testing systems report results as a Personal Attenuation Rating (PAR), which is a single-number value representing the overall sound reduction across frequency bands for that particular fitting of the protector on the person being tested. A few systems report results as pass/fail, indicating that a certain level of attenuation (e.g., 15 dB) has been achieved or not.

However, most systems have one or more disadvantages which may hinder implementation. For example, the amount of time needed to conduct the test, limitations regarding the types of HPDs that can be tested, inability to test ears independently, and the need for specialized equipment may present barriers for some companies. To address these issues, NIOSH developed the HPD Well-Fit system. HPD Well-Fit uses digital signal generation to replace the external attenuator box and uses the computer mouse as a response device. HPD Well-Fit requires no specialized equipment beyond a Windows-based computer with a 24-bit audio card, a mouse with a scroll wheel, and a set of large volume headphones. HPD Well-Fit can test any earplug and provides a quantitative measure of sound reduction. The HPD Well-Fit system was licensed by Michael and Associates and is currently sold as FitCheck Solo.[178]

NIOSH and others have used HPD Well-Fit in studies of sandblasters, brewery workers, and oil rig inspectors. Data from the oil rig inspectors illustrate the impact of HPD fit testing (see Fig. 12). Less than 50% of the inspectors tested showed sufficient attenuation at their initial fit test to reduce their noise

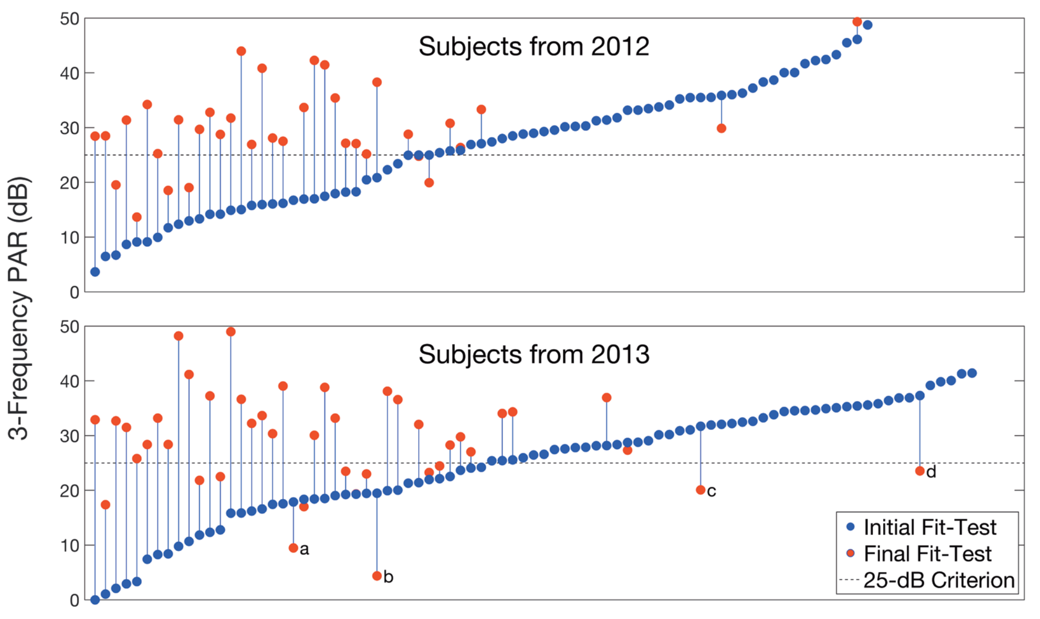

Figure 12 Initial and final personal attenuation ratings (PARs) for oil rig inspectors fit-tested in 2012 and 2013. Blue (darker) dots represent the initial PAR. Workers who did not obtain the target PAR of 25 dB (represented by the horizontal line) were trained and/or fit with alternative hearing protection devices (HPDs). Red (lighter) dots represent the final fit-test result. Subjects in 2013 labeled a and b could not attain PAR with any tested earplug. Subjects labeled c and d wanted to try other HPDs but found they did not receive as much attenuation.

exposures to below 85 dBA. However, following training and/or fitting with alternative HPDs, 89% of the inspectors achieved protected exposure levels below the REL.[178]

Ototoxicity Update

During the 2000s, NIOSH entered into an agreement with the Nordic Expert Group for Criteria Documentation of Health Risks from Chemicals (NEG)—a group of scientific experts from Nordic nations which produces criteria documents to provide a scientific basis for establishing chemical exposure limits—to develop a document on the auditory effects of chemicals. Unlike NIOSH criteria documents, which specify quantitative RELs, NEG criteria documents focus on describing dose–response relationships and defining a critical effect. Published in 2010, NEG document *142: Occupational Exposure to Chemicals and Hearing Impairment* comprehensively reviewed all available evidence for any chemical that had been shown to have a potential association with auditory damage, including pharmaceuticals, organic solvents, metals, asphyxiants, and miscellaneous substances.[11]

Because the strength of evidence for ototoxicity varied across chemicals, the NEG document categorized substances into three groups defined by the type of available evidence. When possible, the document reported the lowest observed adverse effect level and no observed adverse effect level for each chemical. It also reviewed evidence of any interactions between the chemical and noise or other exposures. This document remains the most comprehensive review of occupational ototoxic substances available today.[11] An updated summary of occupational ototoxicity is being published concurrently in this issue of *Seminars in Hearing*.[179]

In 2018, NIOSH collaborated with OSHA to publish a short summary document on ototoxicity. The joint information bulletin, *Preventing Hearing Loss Caused by Chemical (Ototoxicity) and Noise Exposure*, describes the effects that chemicals can have on hearing, identifies chemicals which are ototoxic, provides examples of industries and occupations in which these exposures might be found, and makes recommendations for prevention. The document is written in lay language and geared toward employers and workers who may not be aware of chemical risks to hearing. It is also an excellent resource for hearing health professionals who are unfamiliar with occupational exposures.[180]

Nonoccupational Noise Program at CDC

While the federal government has had a clear program for addressing occupational noise for well over five decades, the workplace is not the only source of hazardous noise. Millions of Americans are routinely exposed to environmental noise sources (e.g., street traffic, airports, nearby industrial plants) and individual noise sources (e.g., personal listening devices, power tools, sporting events).[181] Twenty-one million U.S. adults who report no exposure to noise at work have audiometric evidence of NIHL.[3] Nonoccupational noise is especially an issue for those who are also exposed to noise or other ototoxicants at work. They are in “double jeopardy.”[54]

In 2016, the National Academies of Sciences, Engineering, and Medicine published a report on hearing health in adults, which included several recommendations directed specifically toward CDC.[182] In response, CDC established a program addressing nonoccupational NIHL within its National Center for Environmental Health (NCEH) and organized an interagency work group (which includes NIOSH) to coordinate CDC activities on preventing NIHL. The CDC NIHL Work Group has been very active, highlighting NIHL through the CDC Vital Signs program[3,183] and Public Health Grand Rounds.[184,185] The nonoccupational NIHL team at NCEH has produced many products to promote hearing loss prevention that are freely available on their website, including fact sheets, posters, infographics, videos, social media content, and even a comic book and accompanying teacher guide geared toward grades 3 to 6.[186]

Table 1 Summary of NIOSH noise and hearing loss prevention activities in various NIOSH divisions and laboratories in 2022

NIOSH organizational unit	Current Noise and Hearing Loss Prevention Activities
Division of Field Studies and Engineering	
Noise and Bioacoustics Team	Research projects geared toward preventing OHL in general industry Update of the NIOSH noise criteria document
OHL Surveillance Program	Ongoing surveillance of OHL across industries and occupations Planning for questionnaire content on occupational exposure to noise and ototoxicants in the 2023 National Health Interview Survey
Hazard Evaluations and Technical Assistance Branch	Response to ongoing requests for assistance regarding noise and ototoxic exposures
Pittsburgh Mining Research Division	Research projects targeted at noise control and hearing loss prevention in the mining sector
Western States Division	Survey of noise hazards, ototoxic exposures, and hearing loss in the oil and gas extraction sector
NORA[a] Hearing Loss Prevention Cross Sector Council	Manage the research agenda for hearing loss prevention across the Institute Special projects in conjunction with intramural and extramural council members, such as HPD fit-testing guidance and OHL prevention videos
Health Communication Specialists	Coordinate NIOSH communication products, including an update to the hearing loss prevention web page, the NIOSH Science Blog, NIOSHnoise Twitter account, and other social media outreach

[a]National Occupational Research Agenda.

IMPACT FOR HEARING HEALTH PROFESSIONALS

Noise is the most common cause of preventable hearing loss among U.S. adults.[3,4] All hearing health professionals have a role to play in reducing its burden. Both the American Speech Language Hearing Association[1] and the American Academy of Audiology[2] define hearing loss prevention as a vital aspect of audiology practice. The total hearing health concept involves integration of OHL prevention with prevention in clinical practice to ensure that everyone enjoys a lifetime of healthy hearing.[105]

NIOSH information and tools can help all hearing health professionals incorporate prevention into their day-to-day work. NIOSH recommendations on noise exposure provide a benchmark for evaluating the noise hazard associated with nonwork activities. Principles of noise reduction apply to any noise source, regardless of whether it is occupational or nonoccupational in nature. The concept of considering noise levels in purchasing decisions applies as much to home power tools and appliances as it does to factory machinery. Tips for selecting and fitting hearing protection are universal, irrespective of the environment in which they will be worn. A list of NIOSH and other CDC resources that are useful for all hearing health professionals can be found in the **Appendix**.

LOOKING BACK AND MOVING FORWARD

As NIOSH enters its sixth decade, the Institute continues its Congressionally mandated tasks of developing recommendations to protect workers, conducting research and surveillance on job-related hazards, training occupational health and safety professionals, and providing consultative services as requested by employers and employees. Noise and hearing loss prevention activities covering each of these mandates are taking place across many areas at NIOSH (see Table 1).

OHL prevention has made great strides in the decades since NIOSH was established. NIOSH recommendations have been used to establish regulations for most industries and have been adopted as best practices by a wide range of professional and consensus organizations—representing audiology, industrial hygiene, nursing, medicine, industry, advocacy groups, and standards setting.[187] Awareness of noise as a hazard has increased, at least in high-noise industries. More workers are enrolled in hearing loss prevention programs. Use of hearing protection is more widespread and fit-test systems enable easy ascertainment of noise reduction attained by individual workers. Occupational safety and health professionals have been alerted to previously overlooked chemical risks to hearing. Information to improve education and training efforts has been made available. Advances in technology have improved hearing protection and enabled anyone to measure their own noise exposure using a smartphone. A cadre of well-trained, dedicated professionals passionate about hearing loss prevention continues to grow. Better surveillance data are available and the risk of hearing impairment is significantly reduced among noise-exposed workers.[159,187]

However, hearing hazards remain prevalent in the workplace. Many recommendations for improving hearing loss prevention efforts and reducing the burden of OHL over the years—such as those recommended in *A Proposed National Strategy for the Prevention of Noise-Induced Hearing Loss*,[54] the National Academies of Science review of the Hearing Loss Prevention Research Program,[13] and the various iterations of the National Occupational Research Agenda[69]—are still very relevant today. Despite substantial improvements in occupational noise and hearing loss surveillance, data are still lacking to answer many questions.[187] An evidence-based, practical impulse/impact noise standard is still needed.[32] Awareness of noise hazards is low in certain industries, and other industries lack regulatory protections.[56,188] U.S. regulatory standards are not updated to reflect relevant improvements in the consensus standards codified at the time the regulations were promulgated. Noise control needs to be given priority over hearing protection as a means of lowering worker exposures.[187]

While rates of OHL have decreased, noise remains a prevalent workplace hazard across many economic sectors in the United States, and OHL is a serious risk for many workers. The NIOSH Hearing Loss Prevention Research Program continues to pursue its mission of developing recommendations, conducting research, providing training, and offering consultation with a vision of making OHL a matter of history. This is a large task, and NIOSH will not be able to do it alone. But with the collaboration of other hearing health professionals, it can be done.

CONFLICT OF INTEREST

None declared.

ACKNOWLEDGEMENTS

The authors thank Rick Davis, John Erdreich, Terry Henderson, Barry Lempert, Mark Stephenson, and Carol Merry Stephenson for their invaluable input on content for this history.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, or the views of Stephenson & Stephenson Research and Consulting, LLC.

REFERENCES

1. American Speech Language Hearing Association. The Audiologist's Role in Occupational Hearing Conservation and Hearing Loss Prevention Programs [Technical Report]. 2004. Accessed May 10, 2023 at: https://www.asha.org/policy/tr2004-00153/
2. American Academy of Audiology. Preventing Noise-Induced Occupational Hearing Loss [Position Statement]. 2003. Accessed May 10, 2023 at: https://www.audiology.org/wp-content/uploads/2021/05/niohlprevention.pdf_53996fb4c1ca13.61907521.pdf

3. Carroll YI, Eichwald J, Scinicariello F, et al. Vital signs: noise-induced hearing loss among adults - United States 2011-2012. MMWR Morb Mortal Wkly Rep 2017;66(05):139–144
4. Le TN, Straatman LV, Lea J, Westerberg B. Current insights in noise-induced hearing loss: a literature review of the underlying mechanism, pathophysiology, asymmetry, and management options. J Otolaryngol Head Neck Surg 2017;46 (01):41
5. Finklea JF, Cohen A, Henderson TL. Joint testimony presented before the Government Regulations Subcommittee of the Senate Small Business Committee, July 23, 1975. NIOSH Publications on Noise and Hearing; 1991
6. Neitzel R, Seixas N, Goldman B, Daniell W. Contributions of non-occupational activities to total noise exposure of construction workers. Ann Occup Hyg 2004;48(05):463–473
7. Flamme GA, Stephenson MR, Deiters K, et al. Typical noise exposure in daily life. Int J Audiol 2012;51(0 1):S3–S11
8. Kerns E, Masterson EA, Themann CL, Calvert GM. Cardiovascular conditions, hearing difficulty, and occupational noise exposure within US industries and occupations. Am J Ind Med 2018; 61(06):477–491
9. Nelson DI, Nelson RY, Concha-Barrientos M, Fingerhut M. The global burden of occupational noise-induced hearing loss. Am J Ind Med 2005; 48(06):446–458
10. Basner M, Babisch W, Davis A, et al. Auditory and non-auditory effects of noise on health. Lancet 2014;383(9925):1325–1332
11. Johnson AC, Morata TC. Occupational exposure to chemicals and hearing impairment. Nordic Expert Group for Criteria Documentation of Health Risks from Chemicals. Accessed May 10, 2023 at: https://gupea.ub.gu.se/bitstream/handle/2077/23240/gupea_2077_23240_1.pdf
12. US Congress. The Occupational Safety and Health Act of 1970. Washington, DC: US Congress; 1970 Public Law 91-596
13. Institute of Medicine and National Research Council. Hearing Loss Research at NIOSH. Committee to Review the NIOSH Hearing Loss Research Program. Report No. 1, Reviews of Research Programs of the National Institute for Occupational Safety and Health. Washington, DC: The National Academies Press; 2006
14. National Institute for Occupational Safety and Health. Hearing Loss Prevention Program. 2022. Accessed May 10, 2023 at: https://www.cdc.gov/niosh/programs/hlp/default.html
15. Washam C. Working toward a new NIOSH. Environ Health Perspect 1996;104(05): 484–486
16. Halperin W, Howard J. Occupational epidemiology and the National Institute for Occupational Safety and Health. MMWR Suppl 2011;60(4, Suppl):97–103
17. Thurston FE. The worker's ear: a history of noise-induced hearing loss. Am J Ind Med 2013;56(03): 367–377
18. Jerger J. Audiology in the USA. San Diego, CA: Plural Publishing; 2009
19. Glorig A. The problem of noise in industry. Am J Public Health 1961;51(09):1338–1346
20. Snyder LP. The National Institute for Occupational Safety and Health: A brief history. Office of the Public Health Service Historian, National Library of Medicine, National Institutes of Health; 1997. Accessed May 10, 2023 at: https://upload.wikimedia.org/wikipedia/commons/2/20/NIOSH_-_A_Brief_History.pdf
21. US Department of Health, Education, and Welfare, Public Health Service, Division of Occupational Safety and Health. A Look at the Division of Occupational Health. Public Health Service Publication no. 1118; 1964
22. Cohen A. U.S. Public Health Service field work on the industrial noise hearing loss problem. Occup Health Rev 1965;17(03):3–10
23. Yaffe CD. A study of industrial noise and hearing loss in a controlled population– a preliminary report. Public Health Rep 1954;69(09):815–817
24. Yaffe CD, Jones HH, Weiss ES. Industrial noise and hearing loss in a controlled population-first report of findings. Am Ind Hyg Assoc J 1958;19 (04):296–312
25. Cohen A, Anticaglia JR, Jones HH. Noise-induced hearing loss. Exposures to steady-state noise. Arch Environ Health 1970;20(05): 614–623
26. Lempert BL, Henderson TL. Occupational Noise and Hearing 1968 to 1972 - A NIOSH Study. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health; 1973. Publication no. 74-116
27. Howard J. NIOSH: A short history. Am J Public Health 2020;110(05):629–630
28. Theman CL, Suter AH, Stephenson MR. National research agenda for the prevention of occupational hearing loss - Part 1. Semin Hear 2013;34 (03):145–207
29. National Institute for Occupational Safety and Health. National Occupational Hazard Survey. Vol. 1: Survey Manual. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention; 1974; DHHS(NIOSH) Publication No. 74-127

30. National Institute for Occupational Safety and Health. Criteria for a Recommended Standard. Occupational Exposure to Noise. National Institute for Occupational Safety and Health, Health Services and Mental Health Administration, Department of Health, Education, and Welfare; 1972; Publication No. HSM 73011001
31. Occupational Safety and Health Administration. Occupational Noise Exposure. 1910.95
32. National Institute for Occupational Safety and Health. Criteria for a Recommended Standard - Occupational Noise Exposure: Revised Criteria 1998. Cincinnati, Ohio: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 1998; DHHS (NIOSH) Publication No. 98–126
33. Flamme GA, Deiters KK, Stephenson MR, et al. Population-based age adjustment tables for use in occupational hearing conservation programs. Int J Audiol 2020;59(Suppl 1):S20–S30
34. Schmidek ME, Layne MA, Lempert BL, Fleming RM. Survey of Hearing Conservation Programs in Industry. Cincinnati, OH: U. S. Department of Health, Education, and Welfare; Public Health Service; Center for Disease Control; National Institute for Occupational Safety and Health; 1975; HEW Publication no. (NIOSH) 75-178
35. Council for Accreditation in Occupational Hearing Conservation. History and Bylaws. 2022. Accessed July 12, 2022 at: https://www.caohc.org/about-caohc/history-and-bylaws
36. National Institute for Occupational Safety and Health. Preventing Occupational Hearing Loss - A Practical Guide. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 1996; DHHS (NIOSH) Publication no. 96-110
37. Salmon V, Mills JS, Petersen AC. Industrial Noise Control Manual. Cincinnati, OH: U.S. Department of Health, Education, and Welfare; Public Health Service; Centers for Disease Control and Prevention; National Institute for Occupational Safety and Health; 1975; DHEW (NIOSH) Publication No. 75–183
38. Jensen P, Jokel CR, Miller LM. Industrial Noise Control Manual. Cincinnati, OH: U.S. Department of Health, Education, and Welfare; Public Health Service; Centers for Disease Control and Prevention; National Institute for Occupational Safety and Health; 1978; DHEW (NIOSH) Publication no. 79–117
39. National Institute for Occupational Safety and Health. Compendium of Materials for Noise Control. Cincinnati, OH: U.S. Department of Health, Education, and Welfare; Public Health Service; Centers for Disease Control and Prevention; National Institute for Occupational Safety and Health; 1975; DHEW (NIOSH) Publication no. 75–165
40. Hedeen RA. Compendium of Materials for Noise Control. Cincinnati, OH: U.S. Department of Health, Education, and Welfare; Public Health Service; Centers for Disease Control and Prevention; National Institute for Occupational Safety and Health; 1980; DHEW (NIOSH) Publication no. 80–116
41. National Institute for Occupational Safety and Health. Implement Engineering Controls. 2023. Accessed July 12, 2023 at: https://www.cdc.gov/niosh/topics/noise/preventoccunoise/implement.html
42. Kroes P, Fleming R, Lempert B. List of Personal Hearing Protectors and Attenuation Data. Cincinnati, OH: U.S. Department of Health, Education, and Welfare; Public Health Service; Centers for Disease Control and Prevention; National Institute for Occupational Safety and Health; 1975; DHEW (NIOSH) Publication no. 76–120
43. Lempert BL. Compendium of Hearing Protection Devices. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 1984; PB84-231288
44. Franks JR, Themann CL, Sherris C. The NIOSH Compendium of Hearing Protection Devices. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 1994; DHHS (NIOSH) Publication no. 94–130
45. American Standards Institute. Method for the measurement of the real-ear attenuation of ear protectors at threshold. ANSI 1957; Z24:22
46. Environmental Protection Agency. Product Noise Labeling: Hearing Protective Devices. 40 CFR Chapter I Subchapter G Part 211 Subpart B
47. Michael PL, Kerlin RL, Bienvenue GR, Prout JH, Shampan JI. A Real-Ear Field Method for the Measurement of the Noise Attenuation of Insert-type Hearing Protectors. Cincinnati, OH: National Institute for Occupational Safety and Health; 2016; DHEW (NIOSH) Publication no. 76-181
48. Edwards RG, Broderson AB, Green WW, Lempert BL. A second field investigation of noise reduction afforded by insert type hearing protectors. Noise Control Eng J 1983;20(01):6015
49. Lempert BL, Edwards RG. Field investigations of noise reduction afforded by insert-type hearing protectors. Am Ind Hyg Assoc J 1983;44(12): 894–902

50. Occupational Safety and Health Administration. OSHA Technical Manual. Section III: Chapter 5- Noise. Appendix F: Noise Reduction Rating. 2022 Accessed May 25, 2023 at: https://www.osha.gov/otm/section-3-health-hazards/chapter-5#appendixf
51. National Institute for Occupational Safety and Health. Health Hazard Evaluations (HHEs). 2022. Accessed May 10, 2023 at: https://www2a.cdc.gov/hhe/search.asp
52. Ramos H, Flesch JP. Health Hazard Evaluation Report 71-1-4. Cincinnati, OH: National Institute for Occupational Safety and Health; 1972 Accessed July 17, 2022 at: https://www.cdc.gov/niosh/hhe/reports/pdfs/71-1-4.pdf
53. Pryor P, Lybarger JA, Colligan M, Donohue MT. Health Hazard Evaluation Determination Report HE 78-134-630. Cincinnati, OH: National Institute for Occupational Safety and Health Accessed July 17, 2022 at: https://www.cdc.gov/niosh/hhe/reports/pdfs/78-134-630.pdf
54. National Institute for Occupational Safety and Health. A Proposed National Strategy for the Prevention of Noise-Induced Hearing Loss. Association of the Schools of Public Health, under a Cooperative Agreement with the National Institute for Occupational Safety and Health; 1988; DHHS (NIOSH) Publication number 89-135
55. National Institute for Occupational Safety and Health. National Occupational Exposure Survey (1981-1983): Estimated Numbers of Employees Potentially Exposed to Specific Agents by 2-digit Standard Industrial Classification (SIC). Accessed July 17, 2022 at: https://web.archive.org/web/20110716084755/http:/www.cdc.gov/noes/
56. Themann CL, Masterson EA. Occupational noise exposure: a review of its effects, epidemiology, and impact with recommendations for reducing its burden. J Acoust Soc Am 2019;146(05):3879–3805
57. Dunn DE. Damage to the cells of the organ of Corti. Semin Hear 1988;9(04):267–278
58. Alter S. Ad media group starts hard-hitting war on drugs. Advert Age 1987
59. Atherley GR, Martin AM. Equivalent-continuous noise level as a measure of injury from impact and impulse noise. Ann Occup Hyg 1971;14(01):11–23
60. Dunn DE, Davis RR, Merry CJ, Franks JR. Hearing loss in the chinchilla from impact and continuous noise exposure. J Acoust Soc Am 1991;90(4, Pt 1):1979–1985
61. Taylor W, Lempert B, Pelmear P, Hemstock I, Kershaw J. Noise levels and hearing thresholds in the drop forging industry. J Acoust Soc Am 1984;76(03):807–819
62. Brueck SE, Eisenberg J, Zechmann E, Murphy WJ, Krieg E, Morata TC. Noise exposure and hearing loss among workers at a hammer forge company. Semin Hear 2023;44(04):485–502
63. Erdreich J. A distribution based definition of impulse noise. J Acoust Soc Am 1986;79(04):990–998
64. Erdreich J. Problems and solutions in impulse noise dosimetry. SV. Sound Vibrat 1984;18(03):28–32
65. Greskevitch MF, Bajpayee SS, Hale JM, Gorce DW, Hearl FJ. Results from the National Occupational Health Survey of Mining (NOHSM). Morgantown, West Virginia: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 1996; DHHS (NIOSH) Publication no. 96-136
66. Mine Safety and Health Administration. Health standards for occupational noise exposure: final rule. Fed Reg 1999;64 FR:49548–49634
67. Mine Safety and Health Administration. Occupational Noise Exposure 1999. 30 CFR Part 62
68. Suter AH, Franks JR. A Practical Guide to Effective Hearing Conservation Programs in the Workplace. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 1990; DHHS (NIOSH) Publication no. 90-120
69. National Institute for Occupational Safety and Health. National Occupational Research Agenda. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 1996; DHHS (NIOSH) Publication no. 96-115
70. Lechliter J. National Institute for Occupational Safety and Health. 50 Years of NIOSH. 2021. Accessed July 17, 2022 at: https://www.cdc.gov/niosh/pdfs/NIOSH-50-Year-Timeline2021.pdf
71. Morata TC, Engel T, Durão A, et al. Hearing loss from combined exposures among petroleum refinery workers. Scand Audiol 1997;26(03):141–149
72. Johnson AC, Morata TC, Lindblad AC, et al. Audiological findings in workers exposed to styrene alone or in concert with noise. Noise Health 2006;8(30):45–57
73. Teixeira CF, Augusto LGDS, Morata TC. Occupational exposure to insecticides and their effects on the auditory system. Noise Health 2002;4(14):31–39
74. Morata TC, Dunn DE, Sieber WK. Occupational exposure to noise and ototoxic organic solvents. Arch Environ Health 1994;49(05):359–365
75. Gwin KK, Wallingford KM, Morata TC, Van Campen LE. Health Hazard Evaluation Report 2000–0110–2849. Cincinnati, OH: National

Institute for Occupational Safety and Health; 2001 Accessed May 10, 2023 at: https://www.cdc.gov/niosh/hhe/reports/pdfs/2000-0110-2849.pdf
76. Chen L, Brueck SE. Health Hazard Evaluation Report 2011-0069-3140. National Institute for Occupational Safety and Health; 2011. Accessed May 10, 2023 at: https://www.cdc.gov/niosh/hhe/reports/pdfs/2011-0069-3140.pdf
77. Carlo RV, Feng HA, Morata TC, Kardous CA. In-Depth Study: An Occupational Exposure Assessment of Styrene and Noise in the Fiber-Reinforced Plastic Boat Manufacturing Industry. Cincinnati, OH: National Institute for Occupational Safety and Health; 2007 Accessed May 10, 2023 at: https://www.cdc.gov/niosh/surveyreports/pdfs/306-16a.pdf
78. Morata TC, Little MB. Suggested guidelines for studying the combined effects of occupational exposure to noise and chemicals on hearing. Noise Health 2002;4(14):73–87
79. U.S. Army. Hearing Conservation Guidelines. Washington, DC: Department of the Army; 1998 Pamphlet 40-501, 3-3
80. U.S. Army. Occupational Ototoxins and Hearing Loss. Aberdeen Proving Ground, Maryland: U.S. Army Center for Health Promotion and Preventive Medicine; 2003; Fact Sheet 51-002-0903
81. American Conference of Governmental Industrial Hygienists. Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices. Cincinnati, OH: ACGIH; 2003
82. ACOEM Noise and Hearing Conservation Committee. ACOEM evidence-based statement: noise-induced hearing loss. J Occup Environ Med 2003;45(06):579–581
83. Ehlers JJ, Graydon PS. Noise-induced hearing loss in agriculture: creating partnerships to overcome barriers and educate the community on prevention. Noise Health 2011;13(51):142–146
84. Beckett WS, Chamberlain D, Hallman E, et al. Hearing conservation for farmers: source apportionment of occupational and environmental factors contributing to hearing loss. J Occup Environ Med 2000;42(08):806–813
85. Pedersen DH, Wilkins JR III, Bean TL, Mitchell GL, Crawford JM, Jones LA. Agricultural hazard data from a population-based survey of cash grain farms: Ohio observations. Appl Occup Environ Hyg 1999;14(05):299–305
86. National Institute for Occupational Safety and Health. They're Your Ears: Protect Them. October 2007. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/docs/2007-175/
87. National Institute for Occupational Safety and Health. Have you heard? Hearing loss caused by farm noise is preventable. Young farmers' guide for selecting and using hearing protection. October 2007. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/docs/2007-176/
88. Occupational Safety and Health Administration. Safety and Health Regulations for Construction: Occupational Noise Exposure. 1926.52
89. Tubbs RL. Memorandum: Close-out of HETA 95-0249; HETA 96-0007: National Institute for Occupational Safety and Health; 2002
90. Stephenson MR. Hearing protection in the 21st century: they're not your father's earplugs anymore. Semin Hear 2009;30(01):56–64
91. Stephenson CM, Stephenson MR. Hearing loss prevention for carpenters: part 1 - using health communication and health promotion models to develop training that works. Noise Health 2011;13(51):113–121
92. National Center for Health Statistics. Prevalence and Characteristics of Persons with Hearing Trouble: United States, 1990-1991. Hyattsville, MD: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Center for Health Statistics; 1994. Series 10, Publication no. 188
93. Morata TC, Themann CL, Randolph RF, Verbsky BL, Byrne DC, Reeves ER. Working in noise with a hearing loss: perceptions from workers, supervisors, and hearing conservation program managers. Ear Hear 2005;26(06):529–545
94. Verbsky BL. Effects of conventional passive earmuffs, uniformly attenuating passive earmuffs, and hearing aids on speech intelligibility in noise. Doctoral dissertation. The Ohio State University; 2002
95. Occupational Safety and Health Administration. Hearing Conservation for the Hearing-Impaired Worker. SHIB 12-27-2005. 2005. Accessed July 31, 2022 at: https://www.osha.gov/sites/default/files/publications/shib122705.pdf
96. Tuchman RJ, Brinkley RF. A History of the Bureau of Mines Pittsburgh Research Center. January 1990. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/mining/works/coversheet1609.html
97. U.S. Congress. Balanced Budget Downpayment Act, I. Washington, DC: US Congress; 1995 Public Law 104-99
98. Smith AK, Spencer ER, Alcorn LA, Kovalchik PG. Underground evaluation of coated flight bars for a continuous mining machine. Paper presented at: Proceedings of InterNoise 2006: The 35th International Congress and Exposition on Noise Control Engineering, December 3-6, 2006, 2007; Honolulu, HI
99. Peterson JS, Azman AS. NIOSH hearing loss prevention program for mining. Semin Hear 2023;44(04):394–411
100. Royster JD, Berger EH, Merry CJ, et al. Development of a new standard laboratory protocol for

estimating the field attenuation of hearing protection devices. Part I. Research of Working Group 11, Accredited Standards Committee S12, Noise. J Acoust Soc Am 1996;99(03):1506–1526
101. Berger EH, Franks JR, Behar A, et al. Development of a new standard laboratory protocol for estimating the field attenuation of hearing protection devices. Part III. The validity of using subject-fit data. J Acoust Soc Am 1998;103(02): 665–672
102. American National Standards Institute. Methods for Measuring the Real-Ear Attenuation of Hearing Protectors. New York: Acoustical Society of America; 1997 ANSI S12.6-1997
103. Environmental Protection Agency. Product noise labeling hearing protection devices. Fed Reg 2009; 74 FR:39149–39196
104. Prince MM, Stayner LT, Smith RJ, Gilbert SJ. A re-examination of risk estimates from the NIOSH Occupational Noise and Hearing Survey (ONHS). J Acoust Soc Am 1997;101(02): 950–963
105. Themann CL, Morata TC, Afanuh S. Using Total Worker Health® Concepts to Address Hearing Health. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 2019. DHHS (NIOSH) Publication number 2019-155
106. Tak S, Davis RR, Calvert GM. Exposure to hazardous workplace noise and use of hearing protection devices among US workers – NHANES, 1999-2004. Am J Ind Med 2009;52(05):358–371
107. Occupational Safety and Health Administration. (OSHA), Department of Labor. Occupational injury and illness recording and reporting requirements. Final rule. Fed Regist 2002;67 (126):44037–44048
108. Hager LD. Recordable hearing loss in the United States 2004. 2006; presentation at the annual conference of the National Hearing Conservation Association, Tampa, FL
109. Office of Disease Prevention and Health Promotion. Healthy People 2020. Occupational Safety and Health. February 6, 2022. Accessed July 31, 2022 at: https://www.healthypeople.gov/2020/topics-objectives/topic/occupational-safety-and-health/objectives
110. Office of Disease Prevention and Health Promotion. Healthy People 2030. *Workplace*. July 31, 2022. Accessed July 31, 2022 at: https://health.gov/healthypeople/objectives-and-data/browse-objectives/workplace
111. Environmental Protection Agency. Workshop on Hearing Protector Devices. March 27-28, 2003. Proceedings prepared by Alice H. Suter, Ph.D. under NIOSH contract order number 0000336337. Washington, DC: National Institute for Occupational Safety and Health; 2003. Accessed May 10, 2022 at: https://www.nonoise.org/epa/hearingpro.pdf
112. Murphy WJ, Byrne DC, Gauger D, et al. Results of the National Institute for Occupational Safety and Health-U.S. Environmental Protection Agency interlaboratory comparison of American National Standards Institute S12.6-1997 Methods A and B. J Acoust Soc Am 2009;125 (05):3262–3277
113. American National Standards Institute. Method for Measuring the Real-Ear Attenuation of Hearing Protectors. New York: Acoustical Society of America; 2008 ANSI S12.6-2008
114. Gauger D, Berger EH. A new hearing protector rating: the noise reduction statistic for use with A weighting (NRS_A). A Report Prepared at the Request of the U.S. Environmental Protection Agency. Indianapolis, IN: Reviewed and approved by ANSI S12/WG11. 1, E•A•R 04-01/HP; 2004
115. American National Standards Institute. Methods of Estimating Effective A-Weighted Sound Pressure Levels When Hearing Protectors Are Worn. New York: Acoustical Society of America; 2007 ANSI S12.68-2007
116. American National Standards Institute. Microphone-In-Real-Ear and Acoustic Test Fixture Methods for the Measurement of Insertion Loss of Circumaural Hearing Protective Devices. New York: Acoustical Society of America; 1995 ANSI S12.42-2095 (R1999)
117. American National Standards Institute. Methods for the Measurement of Insertion Loss of Hearing Protective Devices in Continuous or Impulsive Noise Using Microphone-In-Real-Ear and Acoustic Test Fixture Procedures. New York: Acoustical Society of America; 2010 ANSI S12.42-2010
118. National Institute for Occupational Safety and Health. HLSim - NIOSH Hearing Loss Simulator. December 2010. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/mining/works/coversheet1820.html
119. National Institute for Occupational Safety and Health. How to Wear Soft Foam Earplugs (Roll-Pull-Hold). March 2003. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/mining/works/coversheet1840.html
120. National Institute for Occupational Safety and Health. Inquiring Ears Want to Know: A Fact Sheet about Your Hearing Test. By Hudak RL, Schulz TY, Randolph RF. November 2007. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/mining/works/coversheet780.html
121. National Institute for Occupational Safety and Health. CAP the Noise to Save your Hearing! By Hudak RL, Margolis KA, Randolph RF. November 2010. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/mining/works/coversheet1703.html

122. National Institute for Occupational Safety and Health. Infographic: Now Hear This! Take Action to Protect Your Hearing. By Azman A. February 2020. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/mining/works/coversheet2139.html
123. Bauer ER, Babich DR. Worker exposure and equipment noise in large surface coal mines. Min Eng 2004;56(04):49–54
124. Bauer ER, Babich DR. Noise assessment of stone/aggregate mines: six case studies. Min Eng. August 2007;59(08):55–63
125. Bauer ER, Spencer ER. Snapshot of noise and worker exposures in sand and gravel operations. Min Eng 2008;60(03):50–57
126. Reinke DC. Technology News 527 - The Partial Cab: A New Noise Engineering Control for Surface Drill Rigs. 2007 Accessed July 31, 2022 at: https://www.cdc.gov/niosh/mining/works/coversheet1325.html
127. Kovalchik PG, Smith A, Matetic R, Peterson J. Noise controls for roof bolting machines. Min Eng 2009;61(01):74–78
128. Lowe MJ, Yantek DS, Yang J, Schuster KC, Mechling JJ. A noise control package for vibrating screens. Noise Control Eng J 2013;61(02):127–144
129. Camargo HE, Peterson JS, Kovalchik PG, Alcorn LA. Acoustic comparison of pneumatic and electric jackleg drills used in the mining industry. 2010; presentation at NOISE-CON 2010: Proceedings of the 2010 National Conference on Noise Control Engineering and 159th Meeting of the Acoustical Society of America, 2010; Baltimore, MD
130. National Institute for Occupational Safety and Health. Noise Control in Underground Metal Mining. By Reeves ER, Randolph RF, Yantek DS, Peterson JS. Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 2009. DHHS (NIOSH) Publication No. 2010-111
131. Rosenstock IM. The health belief model and preventive health behavior. Health Educ Monogr 1974;2:354–386
132. Joseph A, Punch J, Stephenson M, Paneth N, Wolfe E, Murphy W. The effects of training format on earplug performance. Int J Audiol 2007;46(10):609–618
133. Murphy WJ, Stephenson MR, Byrne DC, Witt B, Duran J. Effects of training on hearing protector attenuation. Noise Health 2011;13(51):132–141
134. Murphy WJ, Gong W, Karch SJ, Federman J, Schulz TY. Personal attenuation ratings versus derated noise reduction ratings for hearing protection devices. J Acoust Soc Am 2022;152(02):1074–1089
135. Safe-In-Sound Excellence in Hearing Loss Prevention Award. 2022. Accessed July 31, 2022: http://safeinsound.us/index.html
136. Meinke DK, Morata TC. Awarding and promoting excellence in hearing loss prevention. Int J Audiol 2012;10(51):S63–S70
137. Morata TC, Meinke D. Uncovering effective strategies for hearing loss prevention. Acoust Aust 2016;44(01):67–75
138. National Institute for Occupational Safety and Health. Notable Milestones in NIOSH History. 2021 Accessed July 31, 2022 at: https://www.cdc.gov/niosh/timeline.html
139. National Institute for Occupational Safety and Health. YouTube. NIOSH. October 19, 2007. Accessed July 31, 2022 at: https://www.youtube.com/user/NIOSHSafetyVideos/about
140. National Institute for Occupational Safety and Health. NIOSH Science Blog: Hearing Loss. May 31, 2022. Accessed July 31, 2022 at: https://blogs.cdc.gov/niosh-science-blog/category/hearing-loss/
141. Shafee T, Masukume G, Kipersztok L, Das D, Häggström M, Heilman J. Evolution of Wikipedia's medical content: past, present and future. J Epidemiol Community Health 2017;71(11):1122–1129
142. Themann CL, Tisdale-Pardi J, Kardous CA, Masterson EA, Morata TC, Murphy WJ. NIOSH noise: a 50-year timeline of research and intervention. NIOSH Science Blog 2022 Accessed July 31, 2022 at: https://blogs.cdc.gov/niosh-science-blog/2022/01/19/noise-50/
143. Ceballos DM, Herrick RF, Carreón T, et al. Expanding reach of occupational health knowledge: contributing subject-matter expertise to Wikipedia as a class assignment. Inquiry 2021;58(Jan-Dec):469580211035735
144. Morata TC, Lum M, Sadowski J, et al. The powerhouse: students' contributions towards expanding and improving occupational safety and health content in Wikipedia. NIOSH Science Blog 2018 Accessed July 31, 2022 at: https://blogs.cdc.gov/niosh-science-blog/2018/07/30/osh-wikipedia2/
145. Webb S, Siordia C, Bertke S, Bartlett D, Reitz D. Artificial intelligence crowdsourcing competition for injury surveillance. NIOSH Science Blog 2020 Accessed July 31, 2022 at: https://blogs.cdc.gov/niosh-science-blog/2020/02/26/ai-crowdsourcing/
146. Howard J. Artificial intelligence: implications for the future of work. NIOSH Science Blog 2019 Accessed July 31, 2022 at: https://blogs.cdc.gov/niosh-science-blog/2019/08/26/ai/
147. National Institute for Occupational Safety and Health. Worker Health Charts. 2022. Accessed July 31, 2022 at: https://wwwn.cdc.gov/niosh-whc/
148. National Institute for Occupational Safety and Health. Prevention through Design: Plan for the

National Initiative: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 2010; DHHS (NIOSH) Publication no. 2011–121
149. Howard J, Murashov M, Cauda E, Snawder J. Advanced sensor technologies and the future of work. NIOSH Science Blog 2021 Accessed July 31, 2022 at: https://blogs.cdc.gov/niosh-science-blog/2021/10/21/sensors-fow/
150. National Institute for Occupational Safety and Health. Productive Aging and Work. November 18, 2018. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/topics/productiveaging/default.html
151. National Institute for Occupational Safety and Health. Safe • Skilled • Ready Workforce Program. May 31, 2022. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/programs/ssrw/
152. National Institute for Occupational Safety and Health. Talking Safety: Teaching Young Workers about Job Safety and Health. July 1, 2014. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/talkingsafety/default.html
153. National Institute for Occupational Safety and Health. Center for Workers' Compensation Studies. April 10, 2020. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/topics/workercomp/cwcs/default.html
154. Masterson EA, Wurzelbacher SJ, Bushnell PT, Tseng CY. Workers' compensation costs for occupational hearing loss claims in the United States, 2009–2013. Semin Hear 2023;44(04):412–436
155. Masterson EA, Tak S, Themann C, Let al. Prevalence of hearing loss in the United States by industry. Am J Ind Med 2013;56(06):670–681
156. General Services Administration, Office of Information and Regulatory Affairs. Unified Agenda of Regulatory and Deregulatory Actions. DOL/OSHA: Noise in Construction. Spring 2016. Accessed July 31, 2022 at: https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=201604&RIN=1218-AD06
157. Masterson EA, Sweeney MH, Deddens JA, Themann CL, Wall DK. Prevalence of workers with shifts in hearing by industry: a comparison of OSHA and NIOSH hearing shift criteria. J Occup Environ Med 2014;56(04):446–455
158. Masterson EA. A story of impact. NIOSH Science Blog 2015 Accessed September 9, 2022 at: http://blogs.cdc.gov/niosh-science-blog/2015/03/25/hl-impact-story/
159. Masterson EA, Deddens JA, Themann CL, Bertke S, Calvert GM. Trends in worker hearing loss by industry sector, 1981-2010. Am J Ind Med 2015;58(04):392–401
160. Sekhon NK, Masterson EA, Themann CL. Prevalence of hearing loss among noise-exposed workers within the services sector, 2006-2015. Int J Audiol 2020;59(12):948–961
161. Masterson EA, Themann CL, Calvert GM. Prevalence of hearing loss among noise-exposed workers within the Health Care and Social Assistance Sector, 2003 to 2012. J Occup Environ Med 2018;60(04):350–356
162. Masterson EA, Themann CL, Calvert GM. Prevalence of hearing loss among noise-exposed workers within the Agriculture, Forestry, Fishing, and Hunting Sector, 2003-2012. Am J Ind Med 2018;61(01):42–50
163. Lawson SM, Masterson EA, Azman AS. Prevalence of hearing loss among noise-exposed workers within the Mining and Oil and Gas Extraction sectors, 2006-2015. Am J Ind Med 2019;62(10):826–837
164. Masterson EA, Themann CL, Luckhaupt SE, Li J, Calvert GM. Hearing difficulty and tinnitus among U.S. workers and non-workers in 2007. Am J Ind Med 2016;59(04):290–300
165. Kardous CA, Shaw PB. So how accurate are these smartphone sound measurement apps? NIOSH Science Blog 2014 Accessed July 31, 2022 at: https://blogs.cdc.gov/niosh-science-blog/2014/04/09/sound-apps/
166. Kardous CA, Shaw PB. Evaluation of smartphone sound measurement applications. J Acoust Soc Am 2014;135(04):EL186–EL192
167. Kardous CA, Shaw PB. Evaluation of smartphone sound measurement applications (apps) using external microphones - a follow-up study. J Acoust Soc Am 2016;140(04):EL327–EL333
168. Kardous CA, Celestina M. New NIOSH sound level meter app. NIOSH Science Blog 2017 Accessed July 31, 2022 at: https://blogs.cdc.gov/niosh-science-blog/2017/01/17/slm-app/
169. Kardous CA, Willson RD, Murphy WJ. Noise dosimeter for monitoring exposure to impulse noise. Appl Acoust 2005;66(08):974–985
170. Price GR, Kalb JT. New approach: the auditory hazard assessment algorithm (AHAA). Paper presented at: International Conference on Biological Effects of Noise, 1998; Australia
171. McGregor KD, Flamme GA, Tasko SM, et al. Acoustic reflexes are common but not pervasive: evidence using a diagnostic middle ear analyser. Int J Audiol 2018;57(Suppl 1):S42–S50
172. Deiters KK, Flamme GA, Tasko SM, et al. Generalizability of clinically measured acoustic reflexes to brief sounds. J Acoust Soc Am 2019;146(05):3993–4006
173. Flamme GA, Deiters KK, Tasko SM. et al. Pervasiveness of early middle ear muscle contractions. Fort Rucker, Alabama: US Army Aeromedical Research Laboratory (USAARL); 2020; Technical Report 2021-05
174. Tubbs RL, Murphy WJ. NIOSH Health Hazard Evaluation Report: Fort Collins Police Services,

Fort Collins, Colorado. Cincinnati, OH: National Institute for Occupational Safety and Health; 2003; HETA #2002-0131-2898
175. Harney J, King B, Tubbs R, et al. Immigration and Naturalization Service (INS) National Firearms Unit (NFU), Altoona, Pennsylvania. Cincinnati, OH: National Institute for Occupational Safety and Health; 2005; HETA #2000-0191-2960.
176. Brueck SE, Eisenberg J, Zechman EL, Murphy WJ, Morata TC, Krieg EF. NIOSH Health Hazard Evaluation Report: Evaluation of Impact and Continuous Noise Exposure, Hearing Loss, Heat Stress, and Whole Body Vibration at a Hammer Forge. Cincinnati, OH: National Institute for Occupational Safety and Health; 2016; HETA #2007-0075
177. Yan HQ, Kardous CA, Murphy WJ. NIOSH Impulsive Noise Measurement System (NIMS). Paper presented at: Proceedings of NOISE-CON, 2004; Baltimore, MD
178. Murphy WJ, Themann CL, Murata TK. Field Testing NIOSH HPD Well-Fit: Off-Shore Oil Rig Inspectors in Texas & Louisiana. Cincinnati, OH: National Institute for Occupational Safety and Health, Division of Applied Research and Technology, Engineering and Physical Hazards Branch; 2015; EPHB Report no. 360-11a
179. Roggia SM, Zucki F, Fuente A, Lacerda A, Gong W, Carlson K, Morata TC. Audiological tests used in the evaluation of the effects of solvents on the human auditory system: a mixed methods review. Semin Hear 2023;44(04):437–469
180. Occupational Safety and Health Administration and the National Institute for Occupational Safety and Health. Preventing Hearing Loss Caused by Chemical (Ototoxicity) and Noise Exposure. DHHS (NIOSH) Publication Number 2018-124. March 2018. Accessed July 31, 2022 at: https://www.cdc.gov/niosh/docs/2018-124/
181. Hammer MS, Swinburn TK, Neitzel RL. Environmental noise pollution in the United States: developing an effective public health response. Environ Health Perspect 2014;122 (02):115–119
182. National Academies of Sciences, Engineering, and Medicine. Hearing Health Care for Adults: Priorities for Improving Access and Affordability. Washington, DC: The National Academies Press; 2016. Accessed May 10, 2023 at: https://doi.org/10.17226/23446
183. CDC. Vital Signs. Too Loud for Too Long: Loud Noise Damages Hearing. February 2017. Accessed July 31, 2022 at: https://www.cdc.gov/vitalsigns/hearingloss/index.html
184. NCEH/ATSDR. Board of Scientific Counselors Meeting Minutes. November 15-16, 2017. Accessed July 31, 2022 at: https://www.atsdr.cdc.gov/science/docs/BSC_Meeting_Minutes_November 2017-508.pdf
185. CDC Public Health Grand Rounds. It's Loud Out There: Hearing Health Across the Lifespan. June 20, 2017. Accessed July 31, 2022 at: https://www.cdc.gov/grand-rounds/pp/2017/201 70620-hearing-health.html
186. National Center for Environmental Health. Hearing Loss Toolkit. 2022. Accessed July 31, 2022 at: https://www.cdc.gov/nceh/hearing_loss/toolkit/index.html
187. Suter AH. The hearing conservation amendment: 25 years later. Noise Health 2009;11(42):2–7
188. Green DR, Masterson EA, Themann CL. Prevalence of hearing protection device non-use among noise-exposed US workers in 2007 and 2014. Am J Ind Med 2021;64(12):1002–1017

APPENDIX: NIOSH RESOURCES FOR HEARING HEALTH PROFESSIONALS

Note: Some resources are available in Spanish. These have been designated by "*en Español*" below the title.

Web Pages

Noise and Hearing Loss Prevention en Español

Main topic page on reducing noise and ototoxic exposures and preventing hearing loss across workers in most industries.

https://www.cdc.gov/niosh/topics/noise

Mining Hearing Loss Prevention Overview

Main topic page on reducing noise and preventing hearing loss in the mining industry. Includes searchable database of mining publications not always available on the main NIOSH page.

https://www.cdc.gov/niosh/mining/topics/HearingLossPreventionOverview.html

Occupational Hearing Loss Surveillance

Web page for the OHL Surveillance Program. Includes statistics on OHL, links to recent publications, and information about partnering with the program.

https://www.cdc.gov/niosh/topics/noise/surveillance.html

NIOSH Science Blogs—Hearing Loss

Summaries and links to all of the blogs relating to noise, ototoxicity, and occupational hearing loss. Links and search engine for blog posts on other topics, including workplace safety in cinema and songs, sports, recycling—even Santa Claus!

https://blogs.cdc.gov/niosh-science-blog/category/hearing-loss/

NIOSH Publications and Products

Searchable bibliographic database of all NIOSH-supported research publications and products.

https://www.cdc.gov/niosh/pubs/

Documents

Criteria Document: Occupational Noise Exposure

NIOSH recommendations for preventing the adverse effects of noise, along with supporting evidence.

https://www.cdc.gov/niosh/docs/98-126/

Preventing Occupational Hearing Loss—A Practical Guide

Summary of best practices for occupational hearing loss prevention programs, with specific recommendations directed toward employers, workers, and program managers.

https://www.cdc.gov/niosh/docs/96-110/

Preventing Hearing Loss Caused by Chemical (Ototoxicity) and Noise Exposure en Español (also available in Portuguese)

Joint OSHA/NIOSH guidance document identifying ototoxic chemicals commonly found in the workplace and providing guidance for preventing their effects on hearing.

https://www.cdc.gov/niosh/docs/2018-124/

Using Total Worker Health Concepts to Address Hearing Health

Guidelines for integrating occupational hearing loss prevention with overall health promotion by extending prevention activities beyond the workplace and considering work-related exposures in the context of overall health.

https://www.cdc.gov/niosh/docs/wp-solutions/2019-155/

Talking Safety: Teaching Young Workers about Job Safety and Health

An introductory curriculum in occupational safety and health for teen workers, customized by state to reflect state-specific labor laws and regulations. Includes section on preventing NIHL.

https://www.cdc.gov/niosh/talkingsafety/

Tools

NIOSH Sound Level Meter App en Español

Information page about the NIOSH noise measurement app for iOS devices. Includes link to the Apple Store page from which the app can be downloaded.

https://www.cdc.gov/niosh/topics/noise/app.html

HLSim—NIOSH Hearing Loss Simulator

Online tool for demonstrating how hearing loss affects the ability to hear speech, music, and machinery in quiet and in background noise. Users can enter specific audiometric thresholds or select from preprogrammed hearing losses.

https://www.cdc.gov/niosh/mining/works/coversheet1820.html

QuickFitWeb

Online tool for screening whether hearing protection is providing at least 15 dB of overall attenuation. Can be downloaded for offline use.

https://www.cdc.gov/niosh/mining/content/quickfitweb.html

Data

NIOSH Health Hazard Evaluation Program Noise Measurement Database

Set of personal and area noise measurements collected during Health Hazard Evaluation (HHE) surveys. In addition to noise data, information on location, industry, type of facility, use of hearing protection, noise generating activities, type of noise (continuous, impulsive, or intermittent), coexisting ototoxic exposures, and other pertinent data are included.

https://www.cdc.gov/niosh/data/datasets/RD-1005-2014-0/

OHL Surveillance Program datasets

Data compiled for certain OHL Surveillance Program analyses are periodically posted for use by external researchers. Data sets include audiometric thresholds, date of test, gender, categorized age, geographical region, and industry classification.

https://www.cdc.gov/niosh/data/datasets/sd-1001-2014-0/default.html

https://www.cdc.gov/niosh/data/datasets/sd-1003-2019-0/default.html

Other CDC Resources on Noise and Hearing Loss

Loud Noise Can Cause Hearing Loss

Main topic page from the National Center for Environmental Health on preventing hearing loss due to nonoccupational noise exposure. Includes a wide variety of tools to assist in prevention efforts, including fact sheets, infographics, posters, videos, animated GIFs, a comic book, and much more.

https://www.cdc.gov/nceh/hearing_loss/default.html

Too Loud! For Too Long! – Loud Noises Damage Hearing

CDC Vital Signs topic page on NIHL. Includes fact sheets, infographics, and brief videos highlighting the problem and easy preventive measures.

https://www.cdc.gov/vitalsigns/hearingloss/index.html

It's Loud Out There: Hearing Health across the Lifespan

CDC Public Health Grand Rounds feature on hearing loss prevention. Includes recordings of the Grand Rounds presentations, an interview with NIOSH scientist Dr. William Murphy, and links to additional resources.

https://www.cdc.gov/grand-rounds/pp/2017/20170620-hearing-health.html