National Research Agenda for the Prevention of Occupational Hearing Loss—Part 1

Christa Themann, M.A.,[2] Alice H. Suter, Ph.D.,[1] and Mark R. Stephenson, Ph.D.[2]

ABSTRACT

The mission of the National Institute for Occupational Safety and Health (NIOSH) is to generate new knowledge in the field of occupational safety and health and to transfer that knowledge into practice for the betterment of workers. Since its establishment in 1970, NIOSH has provided national and world leadership in efforts to prevent occupational hearing loss. In 1996, NIOSH established the National Occupational Research Agenda (NORA). Because occupational hearing loss is one of the most common occupational illnesses among American workers, it was identified as a priority research area, and a NORA Hearing Loss Team was established. The NORA Hearing Loss Team was composed of representatives from industry, academia, labor, professional organizations, and other governmental agencies. The team was tasked with developing a national research agenda for the prevention of occupational hearing loss. Each team member contributed to the original draft, which continued to evolve over time. The current document represents the culmination of several years of deliberation and revision with the goal of identifying needed research to prevent occupational hearing loss. This is Part 1 of the document, outlining research needs on the mechanisms and consequences of occupational exposure to noise and other ototoxicants.

KEYWORDS: Occupational hearing loss, hearing conservation, hearing loss prevention, noise exposure

DEFINING THE PROBLEM

Preventing hearing loss and other adverse effects of occupational exposure to noise and ototoxic agents requires an understanding of the extent of the problem, the mechanisms that underlie these effects, the factors that contribute to their development or prevention, and their consequences.

[1]Alice Suter & Associates, Portland, Oregon; [2]National Institute for Occupational Safety and Health, Cincinnati, Ohio.

Address for correspondence: Mark R. Stephenson, Ph.D., National Institute for Occupational Safety and Health, 4676 Columbia Parkway, Cincinnati, OH 45226 (e-mail: mos9@cdc.gov).

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Although hearing loss has been recognized as an occupational hazard since the earliest days of industrialization, the magnitude of the problem in terms of number of workers exposed, prevalence of resulting impairment, and economic consequences has been estimated but not always well quantified. In addition, there is still much to learn about the impact of occupational noise and hearing loss on job performance, communication, and safety. A better understanding of these factors could help raise the sense of urgency that has been lacking for eliminating this preventable occupational injury.

Furthermore, defining the mechanisms by which noise and chemicals lead to hearing loss and tinnitus is an important step in developing new preventive strategies. Identifying factors that affect or alter susceptibility to hearing damage may open additional avenues for reducing risk. Understanding other extra-auditory effects of noise exposure may provide additional impetus for reducing this hazard in the workplace.

This section of the white paper outlines what we know, what we don't know, and what we need to know to better understand the scope of the occupational noise problem. Although research on these issues will not directly reduce occupational hearing loss and other adverse effects of noise exposure, it will provide the underpinnings necessary to better address the problem. Defining the problem must occur in concert with addressing it.

Prevalence of Noise Exposure in the Workplace

Learning Outcomes: As a result of this activity, the participant will be able to identify the magnitude of the problem of occupational hearing loss.

By one conservative estimate, in the United States ~9 million workers are exposed to daily average sound levels of 85 dBA (decibels measured on an A-weighted scale) and above. The numbers of noise-exposed workers in various types of occupations[1–3] are shown in Table 1. Although these data are now more than 25 years old (with the exception of mining), no surveys of noise exposure have effectively replaced them.

There have been sporadic efforts to document the prevalence of occupational noise exposure and/or hearing loss. These efforts have generally involved examination of noise and hearing loss separately, precluding the ability to link exposure and health outcomes in the same population. Different studies have often used differing protocols, making it difficult to draw accurate conclusions about trends.

Shortly after the passage of the Occupational Safety and Health Act, the National Institute for Occupational Safety and Health (NIOSH) launched the National Occupational Hazard Survey (NOHS) in response to the lack of information regarding safety conditions in U.S. workplaces. The survey was conducted from 1972 through 1974 across a representative sample of manufacturing and nonmanufacturing workplaces. Surveyors made noise measurements at the employee's ear and recorded the exposure level (or range of levels) whenever continuous noise equaled or exceeded 85 dBA. Exposures were recorded regardless of duration, provided the activity causing the exposure was routine. Impact noise was noted when peaks exceeded 130 dBC (decibels measured on a C-weighted scale) and occurred at intervals greater than 1 second. Potential exposures were recorded when noise levels seemed excessive but measurement was impractical.[4] The survey estimated that over 7,500,000 workers were potentially exposed to hazardous noise, including 23% of all employees in manufacturing.

Table 1 Numbers of Workers Exposed to Noise in Various Industries

Industry	Estimated No. of Exposed Workers
Agriculture	323,000
Mining	218,400
Construction	513,000
Manufacturing and utilities	5,124,000
Transportation	1,934,000
Military	976,000
Total	9,088,400

Sources: All estimates, except for mining, are from Simpson and Bruce.[1] Mining estimates are from the Mine Safety and Health Administration[2] and the National Institute for Occupational Safety and Health.[3]

In 1976, the U.S. Department of Labor contracted with Bolt, Beranek, and Newman, Inc. (BBN) to conduct an economic analysis of proposed changes to the noise regulation. The project was limited to the manufacturing sector and included an estimation of the number of workers exposed to various noise levels. The measurement protocol accounted for duration of exposure and reported exposure levels in terms of an 8-hour time-weighted average (TWA). Even so, the study revealed that 34% of manufacturing workers were exposed to sound levels in excess of 85 dBA, an estimate well above the 23% found in the NOHS. The analysis also showed that 19% of manufacturing workers were exposed to levels above 90 dBA, 8.3% were exposed to levels above 95 dBA, and nearly 3% had exposures above 100 dBA.[5]

As a result of the BBN analysis, the Occupational Safety and Health Administration (OSHA) estimated the distribution of noise exposure among ~15 million workers in the manufacturing industries,[6] as shown in Table 2.

The degree to which these estimates apply to other types of industry is unknown, and it is uncertain whether they would be valid with regard to manufacturing today.

NIOSH conducted a second survey of workplace hazards, known as the National Occupational Exposure Survey (NOES), from 1981 to 1983. The measurement protocol was

Table 2 Exposure of Manufacturing Workers to Various Occupational Noise Levels, as Estimated by OSHA in 1981

Exposure Level (dBA)	Percentage of Workers Exposed
<80	46.9
80–85	18.7
85–90	15.1
90–95	11.0
95–100	5.4
>100	2.9
Total	100

dBA, decibels measured on an A-weighted scale; OSHA, Occupational Safety and Health Administration.

similar to that used in the NOHS. However, surveyors did not record the actual noise measurements; they simply recorded the presence of the exposure if continuous noise was equal to or greater than 85 dBA or impact noise peaks were greater than 130 dBC. Duration was not considered in the sense of a TWA, but exposures were classified as either full-time or part-time.[7] The NOES estimated that 17% of manufacturing workers were exposed to hazardous noise levels (unpublished data from NOES database).

Most of the more recent estimates of noise exposure have concentrated on occupations other than manufacturing. The National Occupational Health Survey of Mining, conducted by NIOSH from1984 to1989, provided very basic data on numbers of miners exposed to hazardous noise levels. No measurements were taken. Surveyors recorded a potential exposure to hazardous noise whenever they had to raise their voice above a normal conversational level. Exposure duration was classified as full-time or part-time. Survey results indicated that ~200,000 mine workers (73%) were exposed to potentially hazardous noise.[3] The Mine Safety and Health Administration (MSHA) has collected noise exposure data over many years of inspections. In the 1999 preamble to its noise regulation, MSHA added information from a study of dual-threshold noise samples in which a dosimeter threshold of either 90 dBA or 80 dBA was used. With the latter threshold, the study revealed that 67% of the samples from metal and nonmetal mines and 77% from the coal industry exceeded the 85-dBA action level.[2] These findings corroborate those of the earlier NIOSH survey.

On the basis of the NIOSH NOES data from the early 1980s, Hattis updated the estimated number of noise-exposed employees in various construction trades to a total of 745,000 exposed at levels (not TWAs) of 85 dBA and above.[8,9] The greatest percentages of construction workers whose exposures exceeded 85 dBA were in the areas of concrete work, carpentry and floor-laying, and highway and street construction. Neitzel and his colleagues at the University of Washington have conducted a series of studies on noise exposure and hearing loss in construction workers.[10,11] Using data-logging dosimeters, they found that with the 5-dBA exchange rate, 40% of their noise samples exceeded the 85-dBA criterion, and with the 3-dBA exchange rate, 80% exceeded the criterion.[10] Again, the numbers of workers considered overexposed can vary according to the measurement method used.

Relatively little attention has been given to noise exposure among agricultural workers until recently, with the publication of several study reports and reviews. Major sources of overexposure appear to be tractors without cabs (or even old tractors with cabs); firearms; workshop tools; small motors (e.g., on chainsaws, augers, and pumps); noisy animals such as pigs (during manual handling); and heavy machinery such as harvesters and bulldozers.[12] A review by McCullagh[13] lists the results of several studies of noise exposure levels, with tractors emerging as the principal source of overexposure, even among farm youths. Most tractors measured emitted noise levels of 90 dBA and above. Solecki[14,15] studied the noise exposure of workers on family farms and found mean exposure levels (in terms of average daily value for equivalent continuous sound level, or L_{eq}) of 90.5 dB and 91.3 dB, depending on the activity. Because Hispanics are often employed in agriculture, the hazards of hearing loss from high noise levels can pose additional barriers to their ability to understand speech and warning signals.[16] (See also "Special Populations" (pgs. 226–229) in Part 2, "Addressing the Problem," for a discussion of issues related to non-native speakers of English.)

Studies of noise exposures in several other occupations have only just begun. For example, in an investigation of noise exposure in commercial fishing, Neitzel and colleagues found that the extended work shifts required of seamen exposed them to noise that nearly always exceeded the relevant limits, and even when the use of hearing protection devices (HPDs) was accounted for, nearly half of the 24-hour exposures exceeded those limits.[17] A study of rail workers at a chemical facility revealed that although full-shift exposures complied with the OSHA permissible exposure limit, impact sound levels exceeded 140 dB in nearly all of the samples, with a mean peak sound level of 143.9 dB.[18]

A recent study by NIOSH shows that the number of overexposed workers may be higher than the original estimate of 9 million. Tak et al[19] analyzed data from the National Health and Nutrition Examination Survey, in which a sample population was asked whether they were exposed to noise on the job that was loud enough to necessitate raising their voices to be heard. The analysis showed a 17.2% weighted prevalence of current hazardous noise exposure, representing ~22.4 million U.S. workers. The highest prevalence was in mining, followed by various types of manufacturing and construction activities. Although self-reported assessments are useful, they must be validated with noise surveys.

Because these surveys have used different methodologies, it is difficult to make comparisons and to look for trends. Moreover, extrapolating from these older studies, some of which were completed more than 20 years ago, is not likely to give an accurate picture of the number of noise-exposed workers today. Updated surveillance data would indeed be helpful, but the lack of it need not impede progress in current preventive strategies, because the number of overexposed workers is obviously very large.

RESEARCH NEEDS

- Conduct surveillance to continually update noise exposure estimates in major sectors of U.S. industry.
- Put special emphasis on noise exposures in traditionally underserved sectors, such as agriculture and construction.

Risk Assessment

Learning Outcomes: As a result of this activity, the participant will be able to describe the policy and technical factors associated with hearing damage-risk criteria.

Assessing the risk of hearing impairment resulting from various noise exposure levels and durations has often been referred to as establishing *damage-risk criteria*. Many factors enter into the development of these criteria in addition to the data on the amount of hearing loss resulting from certain levels and durations of noise exposure. There are both technical and policy considerations affecting the development of criteria and their application to standards and regulations. The following questions are good examples of policy considerations: What proportion of the noise-exposed population should be protected, and how much hearing loss constitutes an acceptable risk? Should we protect even the most sensitive members of the exposed population against any loss of hearing, should we protect against only a compensable hearing handicap, or should we protect against some amount of hearing impairment that lies between these two extremes? The selected level of impairment is often termed *material impairment of hearing*. The answers to these questions are related, at least in part, to the hearing loss formula that is used, and different governmental bodies and consensus organizations have varied widely in their selections.

In earlier years, regulatory decisions were made that allowed substantial amounts of hearing loss as an acceptable risk. The most common definition of material hearing impairment (or hearing handicap) used to be an average hearing threshold level or "low fence" of 25 dB or greater at the audiometric frequencies 500, 1000, and 2000 Hz. Definitions have become more restrictive over time, with different governmental agencies or consensus groups advocating different definitions. For example, one U.S. government agency now uses a 25-dB average at 1000, 2000, and 3000 Hz,[6] and another uses the same low fence averaged over the frequencies 1000, 2000, 3000, and 4000 Hz.[20] Other definitions may incorporate a low fence of 20 dB or 30 dB and may include a different frequency combination or a broader range of frequencies.

Table 3, from the 1998 NIOSH criteria document for noise, shows the percentage of "excess risk" predicted to occur over a working lifetime from average noise levels of 90, 85, and 80 dBA, as determined by various agencies.[20] Excess risk is the percentage of the exposed population expected to exceed the 25-dB low fence at certain audiometric frequencies, after subtracting those who would exceed the fence naturally from the aging process.

Although the predicted risk is somewhat dependent upon the frequency combination used to represent material impairment of hearing, inspection of Table 3 reveals that other

Table 3 Estimates (%) of Excess Risk over a Working Lifetime, Adjusted for Aging

	Definition of Material Impairment									
	0.5-1-2k Hz definition					1-2-3k Hz definition			1-2-3-4k Hz definition	
Average Exposure Level, dBA	1971 ISO	1972 NIOSH	1973 EPA	1990 ISO	1997 NIOSH	1972 NIOSH	1990 ISO	1997 NIOSH	1990 ISO	1997 NIOSH
90	21	29	22	3	23	29	14	32	17	25
85	10	15	12	1	10	16	4	14	6	8
80	0	3	5	0	4	3	0	5	1	1

dBA, decibels measured on an A-weighted scale; EPA, Environmental Protection Agency; ISO, International Organization for Standardization; NIOSH, the National Institute for Occupational Safety and Health.

factors affect the prediction. One can see that the NIOSH and International Organization for Standardization (ISO) predictions differ widely, even while using the same frequency formula. These differences can be due to such factors as the noise-exposed databases used, the selection of the non–noise-exposed population for comparison purposes, and the rigor with which both populations are screened. For example, the 1971 ISO standard incorporated the minimally screened data of Baughn, and the Environmental Protection Agency included the Baughn data as well as the more heavily screened data of Burns and Robinson and Passchier-Vermeer.[21,22] The Baughn data were later excluded by the ISO, and NIOSH relied exclusively on its own noise exposure data to develop its earlier damage-risk criteria.

In general, as definitions include higher frequencies and lower fences or hearing threshold levels, the acceptable risk becomes more stringent and a higher percentage of the exposed population will appear to be at risk from given levels of noise. If there is to be no risk of any hearing loss from noise exposure, even in the most sensitive members of the exposed population, then the permissible 8-hour average exposure limit would have to be as low as 75 dBA.[23] In fact, the European Union has established an average exposure level of 80 dBA as its "lower exposure action level" at which employers must make hearing protectors available to workers.[24]

Overall, the prevailing thought on this subject is that it is acceptable for a noise-exposed workforce to lose a small amount of hearing, but not too much. There is no consensus at this time for how much is too much. Those who draft standards and regulations attempt to keep the risk at a minimum while taking technical and economic feasibility into account, but without coming to consensus on such matters as the frequencies, low fence cutoff, or percentage of the population to be protected. Although these issues should be further explored, they remain policy rather than scientific questions.

In addition to the above issues, the assessment of risk is influenced by the method of exposure measurement. If a population's noise exposure is measured (or estimated) with use of a 5-dB exchange rate, then the predicted risk will usually be lower than if the 3-dB rule is used. Comparing a population whose noise exposure is assessed by means of the OSHA 5-dB exchange rate with the original exposed populations in the above damage-risk criteria would be erroneous, because those of the original studies were measured by means of the 3-dB rule. Daniell and coinvestigators found that the percentage of workers exceeding a given noise exposure criterion was 1.5 to 3 times higher with the 3-dB than the 5-dB exchange rate.[25] Research by Robinson,[26] Neitzel et al,[27] and others has shown that the difference in TWA exposure levels between the 5-dB and 3-dB exchange rates in various conditions can be as great as 8 to 10 dB. Consensus organizations,[28,29] certain governmental agencies,[20,22,23,30,31] and a vast majority of nations throughout the world[32] have adopted the 3-dB exchange rate as a more accurate and protective method of assessing the risk of noise exposure. However, because the 5-dB exchange rate is specified in OSHA's noise regulation,[6] most American employers have assessed the risk of their workers by means of the 5-dB rule. It would be helpful to have a method by which existing noise exposure data could be converted, or at least estimated, from the 5-dB to the 3-dB exchange rate, but no such method is available. Because nearly all contemporary dosimeters are able to measure by both methods simultaneously, it would be feasible to collect the data necessary to develop this conversion method, so long as the data using both time functions are retained.[33]

Most of these risk assessments were performed on relatively stable populations many years ago, when noise measurement and audiological practices were not as sophisticated as they are today. Also, most of the workers who were subjects in these studies had not yet begun to wear HPDs. Although it would be useful to conduct large-scale noise exposure studies with modern equipment and practices, the current widespread use of HPDs would compromise the resulting hearing loss data to an unknown and largely uncontrollable extent. It is possible that studies of this kind could be considered in developing, rapidly industrializing nations, but *only* if such studies were not to the detriment of an unprotected workforce.

Several recent studies have indicated that workers with moderate noise exposure levels, calculated at either the 5-dB or 3-dB exchange rate, are at greater risk of hearing impairment than previously thought.[23,34,35] For example, Rabinowitz and coauthors[35] studied a large population of aluminum workers and found that workers with TWA exposures around 90 dBA had fewer age-adjusted standard threshold shifts than those with lower exposure levels. After examining several possible confounding variables, they concluded that the greatest burden of preventable occupational hearing loss occurred in workers whose exposures averaged 85 dBA or less. The principal reason for this finding was thought to be the success of the company's hearing protection program, requiring and enforcing the use of HPDs at higher levels but not at levels below 85 dBA.

Because government and consensus organizations have paid relatively little attention to the risk of occupational exposures at average levels below 85 dBA, additional research would be useful to gain more information about risk in various unprotected worker populations exposed to moderate levels and durations of noise in various patterns of exposure.

Nontraditional work shifts, such as 10-, 12-, and even 24-hour shifts, are becoming increasingly common in some types of occupations. Because these exposure periods may give less opportunity for complete recovery from temporary threshold shift (TTS), more information is needed to assess whether the 3-dB exchange rate is appropriate or whether an adjustment or another method of calculation is needed.

Noise exposure assessments by means of either the 5-dB or 3-dB exchange rate appear inadequate to assess the resulting hearing impairment in occupations characterized by short-duration, high-level exposures, such as firefighting and operation of emergency vehicles.[34] Sometimes the outcome of high-level, short-duration noise bursts can be acoustic trauma. An example is direct exposure to the ringing of cordless telephones; several years ago, exposures to levels of ~123 to 135 dB for only a few seconds appeared to cause hearing loss in some people.[36] The existence of these types of exposures raises questions about the ceiling or not-to-exceed levels, in terms of both sound level and sound duration—questions that need further study in occupational populations.

Consensus standards for noise exposure and hearing loss predictions, such as ISO 1999[37] and American National Standards Institute (ANSI) S3.44,[38] are often used to predict the risk of a workforce exposed to given levels of noise. These predictions can be made if the comparison population is suitably matched in terms of age, gender, nonoccupational exposure, and other factors. One factor that is often overlooked is the effect of audiometric experience or "learning" on hearing threshold level. Whereas most of the early studies reflect thresholds that were taken only once, often noise-exposed comparison populations have been tested many times. Royster et al[39,40] found that the learning effect can reduce hearing threshold level by 5 to 8 dB, depending upon frequency. Other investigators have found slightly smaller effects.[41] The number of years during which the learning effect takes place and the amount and conditions of improvement need to be studied more carefully if accurate population comparisons are to be made.

Data from non–noise-exposed comparison populations that include information on the learning effect have recently become available, as have data on the hearing threshold levels of older workers, which have been lacking in previous studies. An example of such a study is the Baltimore Longitudinal Study of Aging.[42,43] Another set of data, from the Framingham Heart Study, provides hearing threshold levels of men and women aged 60 to 95 years.[44] A longitudinal follow-up study of the same population shows that although hearing threshold levels decreased over a 6-year period, age alone accounted for only 10% of the variance.[45]

Other studies yielding normative data have recently been published by research teams in Europe and the United Kingdom.[46–48] The Engdahl (Norwegian) study compared the effects on hearing thresholds of population screening for nonoccupational noise exposure and otological abnormalities and found little effect on the median hearing threshold levels of young adults but a substantial effect on the thresholds of men over 40 years of age. The authors reported that both screened and unscreened median thresholds exceeded the levels of those published in ISO 7029, which is thought to be highly screened,[49] but they made no comparisons to Annex B of ISO 1999[37] and ANSI S3.44,[38] which is commonly used in the United States.

In the United Kingdom, a study of a randomly selected unscreened population, some of whom reported exposure to occupational or nonoccupational noise, showed hearing threshold levels in the high frequencies (4 to 6 kHz) that were similar to those of ISO 7029 or slightly exceeded them.[47] More recently, a Swedish population, unscreened except for exposure to occupational noise, showed high-frequency hearing threshold levels that were very similar to those of ISO 7029.[48] However, the extent to which the European populations are comparable to U.S. non–noise-exposed groups is not clear.

At NIOSH, Prince and coworkers[50] investigated the effect of adding back earlier data that had previously been screened from their non–noise-exposed cohort and found results that were similar to those of Annex B, at least for ages less than 60 years. Because the data in Annex B are more than 40 years old and do not exclude all cases of occupational exposure, additional normative data that would be directly applicable to today's occupationally exposed populations would be helpful. One such study has made use of data from the National Health and Nutrition Examination Survey (NHANES) of 1999 to 2004 and revealed somewhat lower (better) thresholds at most frequencies than those in Annex B.[51] An advantage to all of the newer data sets is that they include hearing threshold levels for ages above 60 years, exceeding the limitations of Annex B and ISO 7029.

Until fairly recently, professionals involved in noise effects and hearing conservation have assumed that after the termination of noise exposure, any deterioration in hearing threshold levels continues only as a result of the aging process.[52] There is research, however, that indicates otherwise. Animal experiments by Morest and Bohne have revealed noise-induced degeneration in the brain as a result of cochlear damage.[53,54] More recently, population studies by Gates et al[45,55] and Rosenhall[56] suggested that the noise-damaged ear does not age at the same rate as the nondamaged ear. They found that although the growth of hearing impairment tends to slow at the most noise-affected frequencies of 3000 to 6000 Hz, the growth of hearing loss appears to accelerate at the neighboring frequencies of 8000 Hz and especially 2000 Hz. Animal studies by Kujawa and Liberman[57,58] confirmed these results and indicated the cause as noise-induced damage to the spiral ganglion cells, even without destruction to the cochlear outer hair cells (OHCs). Thus, the risk of early noise exposure, even if resulting in negligible hearing loss and seemingly complete recovery from TTS, can have consequences in later life. Further research is needed to elucidate this process in both animal and human populations. (See additional discussion of susceptibility in "Factors Influencing Susceptibility," pgs. 168–170)

The effects of risk factors besides or in addition to noise continue to be of interest to the research community, although the effects and mechanisms of many of these factors remain poorly understood. Large data pools, such as from the Health, Aging and Body Composition Study,[59] provide opportunities to study an assortment of risk factors in addition to or in combination with occupational noise exposure. In a study of adults aged 73 to 84 years, Helzner et al[59] found that, consistent with previous research findings (e.g., Royster et al[40]), race showed a protective effect for African-American men and women. The authors hypothesize that this is due to larger quantities of melanin in the cochlear hair cells of dark-eyed people as well as higher levels of bone marrow density. Cardiovascular disease was associated with hearing loss only in African-American men, and no relationship was found between hearing loss and self-reported hypertension. Although other studies have shown a higher prevalence of hearing loss in men than in women,[42,43] the analysis of Helzner et al[59] did not support this finding after accounting for occupational noise exposure. Further research on the effects of hypertension and cardiovascular disease, especially as they interact with noise exposure, would be warranted (see additional discussion of risk factors in "Factors Influencing Susceptibility," pgs. 168–170).

The role of cigarette smoking in hearing loss among industrial workers also has been debated. Some studies have shown a higher incidence of hearing loss among smokers than among nonsmokers,[60,61] although a study by Gates et al[62] did not. Mizoue et al[63] studied the combined effects of smoking and occupational noise and found that the prevalence rate of hearing loss associated with smoking plus noise was significantly higher than the rate for either smoking or noise alone. Research to tease out the effects of the above risk factors, especially when combined with noise exposure, would be useful.

RESEARCH NEEDS

- Study further the differences in risk assessment with use of the 5-dB versus 3-dB exchange rate, in an effort to develop a method or guideline for converting exposures based on the 5-dB rule to those based on the 3-dB rule.
- Continue research to establish damage-risk criteria for hearing loss among workers exposed to average levels below 90 dBA.
- Research the effects of nontraditional occupational exposures, including short-duration, high-level (nonimpulsive) noise.
- Study further the non–noise-exposed comparison populations in the United States, with an emphasis on hearing levels of people greater than 60 years of age.
- Define how non-noise risk factors are related to occupational noise exposure and resulting hearing loss.
- By means of laboratory and field research, further elucidate the effects of early noise exposure on the aging process of the auditory system.

Impulse/Impact Noise

Learning Outcomes: As a result of this activity, the participant will be able to identify the nature of and the methods used to assess the hearing hazard posed by impulse/impact noise.

Impulse noise has long been a particularly intractable problem for researchers in noise-induced hearing loss (NIHL), not only in terms of its effect on hearing but also in the ability to measure it and even the ability of professionals in the field to agree on a definition. Much of the impetus for early work in this area has been from the damaging effects of noise exposures in the military. According to Fausti et al,[64] 65% of combat injuries between 2003 and 2005 were caused by explosions, and up to half of these incidents led to NIHL, with the possibility of damage to the central auditory system as well as to the cochlea. Gunfire also has been a prevalent source of hazardous noise exposure in the military, among civilians who hunt and target shoot, and in certain occupations such as law enforcement. There are many nonoccupational sources of impulse noise, including toys, hand-tools, firecrackers, and air bags, to name just a few. Occupational sources of impulse noise often take the form of impulse noise superimposed on a background of continuous noise, which occurs in many types of industries, such as forging, metalworking, food processing, and the construction trades. Because these impulsive events are longer in duration and often different in character from gunfire or blast noise, they are usually called *impacts* rather than *impulses*. Both types of acoustic events may be referred to as *transients*, and when transients are superimposed on a background of continuous noise, which is often the case in industry, the result may be called *complex noise*.

Professionals in acoustics have struggled over a definition of impulse/impact noise for decades. In 1969, the U.S. Department of Labor defined impulse noise by default. Section (b)(2) of its early noise regulation states that if variations in noise level involve maxima at intervals of 1 second or less, then the noise is considered continuous.[65] Thus, impulse noise, which has a recommended limit of 140-dB peak sound pressure level (SPL), may be considered a transient, with maxima occurring less often than one per second. This part of the regulation is still in effect today.[66] Later, in its amendment to the noise standard for hearing conservation programs, OSHA gave no further definition of impulse noise, but section (g)(2)(b) requires all continuous, intermittent, and impulsive sound levels from 80 to 130 dB to be integrated into the computation of the 8-hour TWA sound level.[6] According to Erdreich,[67] these early definitions have their foundation in noise-measuring instruments rather than in the mechanisms of hearing damage.

Coles et al[68] referred to the following as important parameters of impulse noise:

- Peak pressure level
- Rise time
- Pressure-wave duration
- Pressure-envelope duration
- Frequency spectrum

Traditionally, the difference between impulse and impact noise has been considered to be that impulse noise is a transient resulting from a sudden release of energy into the atmosphere, and impact noise is a transient resulting from the impact between two objects. An important distinction between the two types was stated in terms of the A-duration (the time from ambient level to the positive peak and return to ambient) and B-duration (the time for which the pressure-envelope fluctuations, both positive and negative, are within 20 dB of the peak SPL). According to Hamernik and Hsueh,[69] the distinction between impulse and impact noise is somewhat artificial because it is the magnitude of the peak overpressures that determines the rules by which the effects on hearing can be assessed.

Experiments by Price[70,71] supported the importance of spectral information in the impulse and the related frequency area on the basilar membrane of the recipient's cochlea. Hamernik et al[72] also pointed out the importance of spectral information in their recommendation that an adjustment of 5 to 10 dB for spectra with peaks at 2 kHz be added to the permissible exposure limit when calculated according to equal energy.

There have been several attempts over the years to develop damage-risk criteria for impact and impulse exposure.[68] British and American studies recommended peak pressure level and duration limits for both A-duration and B-duration impulses. The Committee on Hearing and Bioacoustics of the National Academy of Sciences built upon the work of Coles et al[68] to propose somewhat more conservative levels for both A-duration and B-duration impulses, recommending a maximum unprotected SPL of 164 dB for very short durations and a floor of 138 dB for B-duration impulses, with a correction factor for the number of impulses other than 100 (i.e., from +10 dB for one impulse to –5 dB for 1000 impulses).[73]

McRobert and Ward[74] proposed criteria for a trading relation between intensity and the number of impulses. Atherley and Martin[75] were among the first to extend the equal-energy rule (L_{eq}) to noise environments with impulse and impact noise. Later, Passchier-Vermeer[76] and others supported the use of L_{eq} in complex noise with an adjustment of +5 dB for impulsive noise.

Several investigations have supported the concept of a critical level, below which TTS grows in an orderly fashion and above which losses grow more rapidly and take longer to recover; the idea is that the mechanism of hearing damage below a certain level is metabolic, whereas above that level it is mechanical. Spoendlin[77] suggested this level to be 130 dB, and Hamernik and Hsueh[69] estimated it to be 140 dB, noting that most industrial impacts would be below that level. Price[78] pointed out that such a critical level would be frequency-dependent, with higher levels being tolerable for transients with predominantly low-frequency components rather than high-frequency components.

In 1981, a meeting of experts was held at the Institute of Sound and Vibration Research in Southampton, England, with a resulting consensus report.[79] The consensus was to accept the A-weighted daily noise exposure on an equal-energy basis for all types of noises having different frequency spectra and time functions, so long as their unweighted instantaneous peak SPL did not exceed 145 dB. The report stated that there was not yet clear evidence to separate impulsive and nonimpulsive noise in terms of effect. The committee recommended field studies on working populations not yet using HPDs, further study on a descriptor of impulsiveness, and noise measurements under HPDs.

In more recent years, several sets of criteria have been developed, mainly for use in predicting hearing damage from weapons noise. The increasing size and sound levels of modern weapons have promoted new concerns about their effects on members of the armed forces. Five major models have emerged:

- MIL-STD-1474D,[80] based on peak SPL, B-duration, and number of impulses. The standard provides specific noise limits for designers and manufacturers supplying equipment and weaponry to the U.S. military. Allowable upper limits are given for a variety of conditions: no hearing protection, single protection, double protection, and nonauditory limits.
- LA_{eq}8hr, developed by a French team,[81,82] is based on the integrated A-weighted sound level for an equivalent 8-hour exposure, adjusted for duration and the number of impulses. A variant of this metric, developed by Hamernik et al,[83] replaced the 8-hour term with a 1-second term in the calculation of equivalent energy. This metric became known as SELA (A-weighted Sound Exposure Level).
- AHAAH, the Auditory Hazard Assessment Algorithm for the Human,[84–86] is an electroacoustic model based on the response to impulsive sound by the cochlea's basilar membrane. The basilar membrane is modeled by a 23-element network transmission time approximating 1/3-octave band intervals. Damage to hearing by an impulse is calculated for each location along the basilar membrane by estimating the resulting displacement. This model includes both a "warned" and "unwarned" condition, depending upon whether the middle-ear muscles have been activated (e.g., by an acoustic reflex) prior to the arrival of the impulse waveform.

- A model developed by Pfander et al[87] and used in Germany incorporates peak pressure, number of impulses, and the "C-duration," which integrates the time in milliseconds where the absolute amplitude of the waveform is within 10 dB of the peak pressure.
- The Smoorenburg model[88] used in the Netherlands incorporates peak pressure, number of impulses, and "D-duration," which is calculated similarly to the B-duration except that the envelope is within 10 dB of the peak SPL rather than 20 dB.

These models have been the subject of discussion and experimentation over recent years. Much of the data used to evaluate them, at least in the United States, were gathered from human volunteer tests referred to as the Blast Overpressure Project (BOP).[89,90] The stimulus represented impulses mainly from large-caliber weapons with high-intensity, low-frequency characteristics. The dependent variable was the TTS, measured 2 minutes after the test, and the subjects wore single HPDs; thus, the BOP studies also provided an opportunity to evaluate the effectiveness of HPDs in high-level impulse noise.[91] The BOP was designed such that any TTS greater than 25 dB was considered an "audiometric failure," and a TTS between 15 and 25 dB was a "conditional failure."[90] Following an audiometric failure, the exposure was decreased by two levels and the number of impulses was increased, or the participant could withdraw altogether. A conditional failure would involve an exposure to at least the next lower peak level, with the number of impulses increased. It would appear that the effect of these "failures" would be to remove some of the more noise-sensitive members of the cohort from the study. Patterson and Johnson[91] identified critical levels of ~184- to 187-dB peak SPL for exposures of 100 impulses; subjects wore earmuffs.

An effort related to the BOP consisted of exposing chinchillas to high levels of impulse noise and observing the TTS, permanent threshold shift (PTS), and anatomical pathology over a wide range of impulse noise exposures.[83]

Chan et al[92] analyzed the criteria of the four NATO countries (the models outlined above, with the exception of AHAAH), correlating each criterion with the BOP data by means of logistic regression. They found that all four criteria overpredicted the auditory effect by 9.6 to 21.2 dB. In a later study, Chan and Ho[93] analyzed the AHAAH model against the same TTS human data from the BOP. As a result, the authors were critical of the AHAAH model, claiming that it could allow dangerously high SPLs of impulse noise, even exceeding 190 dB, that the predictive model failed to show a monotonic correlation with the adverse auditory effect, and that the model could even predict an inverse relationship between increasing peak level and hearing hazard.[93]

In a subsequent investigation, Chan and Ho[94] examined the LA_{eq}8hr variant of SELA and tested it against the chinchilla data set of some 900 ears from the BOP. Statistical analysis of the SELA metric, along with the MIL-STD, Pfander, and Smoorenburg models, showed that SELA best predicted TTS and PTS in the BOP chinchilla. The authors proposed a 10-dB upward adjustment in the SELA to apply to humans. For future study, they recommended that any impulse noise injury model should include prediction of recovery time and audiometric frequencies in addition to the averaged 1, 2, and 4 kHz that were examined in this analysis.[94]

Further efforts to find the most effective metric for evaluating hearing damage have been conducted by Murphy and colleagues at NIOSH.[95,96] Recently the team evaluated six potential metrics for goodness of fit and discrimination: MIL-STD 1474 D, LA_{eq}8hr, AHAAH in the warned and unwarned condition, and the Pfander and Smoorenburg models.[96] The chinchilla data and impulsive stimuli were derived from the data of Hamernik et al[83] and Patterson et al.[97] Exposures were varied in terms of peak level, number of impulses, and temporal spacing, and for each exposure condition a representative waveform was digitally recorded and archived along with auditory evoked potentials, TTS, PTS, and histological data from each animal. The results of this analysis showed that the LA_{eq}8hr metric provided the best fit to the TTS and PTS data. The Pfander and Smoorenburg models ranked second and third, respectively, and the MIL-STD was the poorest. The $LA_{eq}8hr$ metric also scored highest in tests for receiver operating characteristic, showing a greater ability to predict whether or not hearing loss would occur. The unwarned condition of the AHAAH model did succeed in providing the best fit to PTS, however.[96]

In another analysis, Murphy et al[95] tested the ability of the MIL-STD, the $LA_{eq}8hr$ (free-field or protected), and the AHAAH warned and unwarned metrics to predict hearing hazard in the human populations exposed in the BOP. This time the metric that yielded the best fit was the free-field $LA_{eq}8hr$, followed by the MIL-STD, the protected $LA_{eq}8hr$, the unwarned AHAAH, and the warned AHAAH. Although the MIL-STD had performed poorly in the previously described study, it was second only to free-field $LA_{eq}8hr$ in this analysis. The authors concluded that the warned condition of the AHAAH model is not realistic for many noise conditions, that further research should include an assumption of HPD attenuation for the MIL-STD that is more realistic than 29 dB, and that the research should concentrate on actual hearing threshold damage risk.[95]

Not long after the Institute of Sound and Vibration Research workshop in Southampton, investigators began to question the use of the equal-energy hypothesis to characterize the effects of all impulse/impact conditions. In a critical review of the impulse noise literature, Henderson and Hamernik[98] cited the finding of Ceypek et al[99] that a combination of impact and continuous noise produced a greater effect than equal energy would predict. They cited the findings of Luz and Hodge[100] that recovery from impulse noise–induced TTS could be erratic and nonmonotonic, and they concluded that temporal pattern, waveform, and rise time are important variables that L_{eq} does not describe.

Perhaps the earliest attempt to use kurtosis as a metric to assess the effect of transients on hearing was proposed by Erdreich,[67] who pointed out that variables such as repetition rate, spectral content, and multiple peaks occurring before reaching the –20-dB point with B-duration pulses were not adequately taken into account by equal-energy or other existing metrics. Kurtosis (β) is defined as the ratio of the fourth-order central moment to the squared second-order central moment of a distribution.[101] The advantage of using kurtosis would be that all peaks would be accounted for as well as the relative difference between peak and background levels. He recommended choosing an arbitrary value of kurtosis, which, when exceeded, would render the noise impulsive in character. For several years, both animal studies[102,103] and epidemiological studies[104–106] had indicated that equal energy is an insufficient predictor of hearing damage from complex noise.

In a remarkable series of experiments, Hamernik and his colleagues at SUNY Plattsburgh explored the use of kurtosis to predict hearing damage in the chinchilla model. They measured the effects in terms of TTS, asymptotic threshold shift, PTS, inner hair cell loss, and OHC loss. The noise stimulus was varied in terms of overall level, background level, peak level, interpeak interval, intermittency schedule, frequency, and frequency bandwidth. Each experiment built upon the findings of the previous one, further refining the role of kurtosis and its modifications as a predictive tool.[101,103,107–109]

With a limited set of exposure parameters, Lei et al[103] introduced high-level transients into Gaussian (G) noise and found that the unfiltered kurtosis metric $\beta(t)$ rank ordered the degree of hearing trauma and that the filtered condition of $\beta(f)$ reflected the frequency specificity of the trauma. Hamernik and Qiu[101] extended the experiment of Lei et al to include more non-G conditions with various peak and background sound levels and broadband noise, all within an overall L_{eq} of 100 dBA. Each non-G exposure produced more hearing damage than the G reference exposure. They found that the magnitude of the damage depended upon frequency content, with OHC loss increasing as the stimulus bandwidth increased. Hamernik et al[107] continued the series by varying the probability of occurrence of the transient, changing the impact interval, peak amplitude, and number of pulses, as well as an additional range of spectra. They found that PTS and OHC loss were monotonically related to β in the range of 3 to 40 ($\beta = 3$ being Gaussian), and that with $\beta > 40$ the degree of trauma remained constant despite changes in the statistical character of the noise. One of their subject groups was exposed to random noise bursts rather than impacts, which produced greater damage than G noise but less than in the impact groups, although the value of β was the same. The investigators concluded that a correction to the L_{eq} for β should depend on whether the noise consisted of simple noise bursts or impacts.[107]

Further animal investigations by Qiu et al[108] compared L_{eq} 90-dBA and 110-dBA conditions to the earlier 100-dBA data and introduced additional frequency bandwidths. They found that at 90 dBA there was no significant difference in response to the G and non-G noise conditions, but above that point, differences were apparent. They also found that limiting the stimulus bandwidth reduced the resulting trauma. Hamernik et al[109] extended the previous studies by adding conditions of non-G interrupted, intermittent, and time-varying noise in a schedule to model an industrial work pattern (8 h/d, 5 d/wk for 3 weeks), plus continuous G and non-G noise 24 h/d for 5 days. They found that temporal variations in level had no effect on hearing trauma, so long as the L_{eq} and β values were the same for both the G and non-G groups. However, increasing the β at fixed energy increased the trauma, as earlier investigations had shown. Between β values of 3 (G), 25, and 50, all with the same intermittency schedule, there was a clear ordering of PTS, inner hair cell loss, and OHC loss, with β50 being associated with the greatest damage.[109]

An epidemiological study of the kurtosis metric was recently conducted on Chinese workers who had not yet begun to wear HPDs.[110] The objective was to initiate the development of dose–response criteria by studying two groups of workers exposed to G (textile) or non-G (metal fabrication) environments. The investigators sought to control the duration of exposure, smoking status, alcohol use, and military or shooting exposures. Annex B of ANSI S3.44 was used to adjust for age and gender, and the dependent variable was prevalence of NIHL at 3, 4, or 6 kHz, equal to or greater than 30 dB. Dosimeters, sampling at a rate of 300 samples per minute, and a sound-level meter were used to collect real-time samples of each subject's noise exposure; the data were recorded and later analyzed. Results were stated in terms of cumulative noise exposure in an attempt to describe the total exposure energy of each subject. The prevalence of NIHL was significantly greater and the curve steeper as a result of the non-G noise, in comparison with the G groups. When the curves were adjusted for the effect of kurtosis ($\beta = 40$), they overlapped.

The results from the China study provide significant support for the series of animal experiments preceding them, but considerably more data need to be collected and refinement needs to take place before the appropriate kurtosis metric can be determined and incorporated into instrumentation. Also, because the number of subjects was relatively small ($n = 32$ for non-G and 163 for G conditions), examination of a much larger population would be useful.

In another recent effort to develop a new noise metric that would assess the effects of complex noise more accurately than equal energy, Zhu et al[111] tested various forms of the SUNY researchers' noise signals against the chinchilla data derived by those investigators. To characterize the noise signal, the authors selected the analytic wavelet transform, which would combine both temporal and frequency characteristics. Out of a total of 14 metrics, those that appeared to best correlate with hearing damage were the L_{eq} calculated as a function of frequency and a modification of the L_{eq} weighting higher SPLs more heavily. In this analysis the kurtosis metric did not perform as well, although none of the correlations was particularly strong. More work of this type could possibly explain these differences.

The accumulated knowledge from the series of animal studies and single human study should have a major impact on the way complex noise environments are measured and how their effects on humans can be evaluated. It is clear that it is insufficient simply to use equal energy to assess the traumatic effects of transients embedded in Gaussian noise. However, before the ideal metric can be identified, further information that will contribute to necessary modifications of the kurtosis metric needs to be obtained, in particular, spectral information.

In summary, it appears that the equal-energy method of assessing hearing damage works well in continuous or normally distributed noise environments and possibly in complex environments with total energy < 90 dBA, but for environments with $L_{eq} > 90$ dBA, another metric is needed. At this time, kurtosis appears to be the most promising. Data from the SUNY chinchilla experiments indicate that the kurtosis metric, in combination with adjustments for frequency spectrum and bandwidth, would be an effective predictor of the traumatic effects of complex noise. The most appropriate damage-risk criteria for weapons noise could use further refinement, although $LA_{eq}8hr$ or the SELA variant seems to do the best job. Further research on this issue would be appropriate and should address the needs of both the military and civilian workers. Additionally, the imposition of impulses or impacts on background noise (i.e., complex noise) represents a widespread and serious hazard, with the likelihood that current measurement instruments and techniques are not sufficiently able to provide metrics that accurately describe the hearing damage risk.

RESEARCH NEEDS

- Study further the kurtosis metric in complex noise environments in human populations. Larger sample sizes and additional variables need to be added to the design of previous studies.
- Compare the results of hearing damage from complex noise assessed by kurtosis to existing damage-risk criteria, for the purpose of recommending appropriate correction factors.
- Conduct surveillance to measure kurtosis in a variety of U.S. industrial populations, to assess the degree to which the effect of complex noise may be underestimated.
- Continue research to refine the role of frequency spectrum and other variables in the characterization of complex noise as it affects hearing.
- Develop and standardize methods of measuring complex noise that best characterize the adverse effects on hearing, including the development of appropriate instrumentation.

Surveillance

Learning Outcomes: As a result of this activity, the participant will be able to describe the types of databases and surveillance activities used to identify and characterize occupational hearing loss.

There can be no effective prevention or control of disease without knowledge of when, where, and under what conditions cases occur.[112] Efforts to prevent occupational NIHL have been hampered by this lack of knowledge. Many noise-exposed U.S. workers have been protected by an occupational noise standard for over 35 years. However, there are few data by which the effectiveness of these and other efforts to prevent NIHL can be measured. The number of workers exposed, the prevalence of resulting impairment, and the economic consequences have not been well quantified. A national surveillance system is necessary to identify populations at risk, evaluate the effectiveness of intervention strategies, and monitor progress in prevention.

NIOSH has long recognized the need for surveillance data, concerning both exposure (noise, ototoxic chemicals) and disease (hearing loss). The first research recommendation cited by NIOSH in its *Proposed National Strategy for the Prevention of Noise-Induced Hearing Loss* was the collection of "regular and accurate statistics . . . to assess the magnitude of the problem and to monitor the effect of various prevention/ intervention efforts."[(113)(p.8)] Throughout the 1990s, several NIOSH documents reiterated the need to track occupational noise exposure and hearing loss data.[20,114,115] Most recently, the Institute of Medicine[116] cited the lack of national surveillance data as a major shortcoming in the NIOSH Hearing Loss Research Program. Professional organizations, state health agencies, and health researchers also have emphasized the necessity of good surveillance data.[117–119] However, national surveillance programs are expensive and labor-intensive. In addition, the potential for litigation and regulatory action serves to discourage employers from voluntarily reporting exposure measurements and audiometric results beyond those dictated by law. To date, the resources and impetus necessary to establish an ongoing national surveillance program for noise exposure and/or occupational hearing loss are not available.

Sporadic attempts have been made over the past 40 years to quantify the extent of noise exposure, occupational hearing loss, and/or preventive efforts. The Occupational Noise and Hearing Survey, conducted from 1968 to 1971, sampled noise exposures in industrial work environments and conducted audiometric testing of both exposed and nonexposed workers.[120] These data provided initial estimates as to the number of noise-exposed workers and formed the basis of the 1972 NIOSH criteria document and (after reanalysis) the 1998 revision of the criteria document.[20,121,122] NIOSH also conducted the National Occupational Hazard Survey (1972 to 1974), the National Occupational Exposure Survey (1981 to 1983), and the National Occupational Health Survey of Mining (1984 to 1989) to estimate the number of workers exposed to hazardous noise levels,[4,7,123] as well as the National Survey of Hearing Conservation Programs in Industry, to document existing preventive activities.[124] However, these studies did not use similar protocols and produced only independent estimates that are not useful for monitoring changes over time.

NIOSH personnel recently studied the trends in noise exposure data among miners between 1987 and 2004.[125] During this period, MSHA had revised its existing regulations for miners with more explicit requirements for engineering noise control and hearing loss prevention programs. The median noise dose declined 67% for surface coal miners and 24% for underground miners, and the use of HPDs increased from 61 to 89%. The authors concluded that the revised noise regulation was largely responsible for these benefits, although they suggested that the beneficial results could be offset somewhat by an increase in shift duration also found during this period. This kind of model would be useful to study the effects of future regulations applying to other noise-exposed populations.

Several national databases have been investigated as possible sources of surveillance data for hearing loss prevention purposes. By federal mandate, the Bureau of Labor Statistics (BLS) compiles and publishes statistics on workplace injuries. Approximately 200,000 workplaces are sampled each year and provide the BLS with information about illnesses and injuries directly from their OSHA record-keeping logs. The utility of BLS data for hearing loss surveillance was minimal until very recently because hearing loss was reported with other repetitive trauma disorders and could not be tracked separately. However, since 2004, hearing losses have been recorded independently on the OSHA 300 log, providing the first opportunity for ongoing surveillance of occupational hearing loss. Approximately 28,000 cases of occupational hearing loss were reported in 2004, nearly 27,000 in 2005, 24,000 in 2006, and 22,000 in 2007.[126–129] Although the utility of BLS data has greatly improved and the BLS is currently the best source of surveillance data on occupational hearing loss, it has serious limitations. First, it does not collect data from certain types of employers, including federal, state, and local governments; small businesses and farms; and the self-employed.[130] In addition, data from industries not covered by the Hearing Conservation Amendment (for example, construction) are suspect because there is no requirement for audiometric testing.[126] Furthermore, economic incentives (such as lower workers' compensation premiums, avoidance of OSHA inspections, and supervisor performance evaluations) encourage underreporting.[118,130] The additional requirement of an average 25-dB impairment before a standard threshold shift is deemed recordable also reduces the number of recorded hearing shifts. Hager[126] has estimated that the BLS figures underestimate the annual incidence of occupational noise–induced threshold shifts by an order of magnitude.

The OSHA Integrated Management Information System (IMIS) contains noise exposure measurements collected during compliance or consultation visits.[131] IMIS was not designed as a surveillance system and is not based on a representative sample of U.S. business establishments. Noise samples are more likely to be collected from larger facilities and places where workers are suspected to have higher exposures. Samples may not be entered into the database if they do not exceed the exposure limit or are not needed in support of a citation. However, it is the only national source of noise exposure measurements collected on an ongoing basis. Analysis of IMIS data from 1979 to 1999 indicated that noise exposures have generally decreased over time.[131] Although Middendorf concluded that OSHA IMIS data can be useful for surveillance purposes, he cautioned that the data must be interpreted in view of the context in which they are collected. He made several recommendations for improving the utility of the IMIS database as a surveillance tool, such as including all noise exposure samples, instituting checks for accuracy, and recording additional data elements such as sample duration, presence of engineering controls, and use of hearing protection.[131] The resulting numbers are necessarily dependent upon current policies for enforcement and consultation.

Tak and Calvert[132] utilized data from the National Health Interview Survey (NHIS) to estimate the prevalence of hearing difficulty among employed individuals and the fraction of cases attributable to work-related exposures. Using data collected from 1997 to 2003, they found that 24% of the hearing difficulties among employed adults were due to occupational noise exposure. Workers in the railroad, mining, and primary metal manufacturing industries and mechanics/repairers, machine operators, and transportation equipment operators had the highest prevalence ratios of hearing difficulty. Some possible evidence for the effectiveness of the hearing conservation amendment was found in the fact that the construction industry—which is covered by the same noise standard but not the same hearing conservation regulations as general industry—had the largest number of workers with hearing loss attributable to employment. Because the NHIS is conducted annually, this type of analysis could be useful in tracking trends in occupational hearing loss. However, because the NHIS collects prevalence data (i.e., existing cases at a given point in time) rather than incidence data (i.e., new cases over a defined period of time), changes over time would be slow to appear. In addition, NHIS data are based on self-reports rather than audiometric testing, and the authors suggest that the prevalence of hearing loss may be underestimated because of the low sensitivity of the question used to define hearing loss.

One example of a comprehensive surveillance program for occupational hearing loss was the Michigan Sentinel Event Notification System for Occupational Risk program. The effort has been funded through the NIOSH Sentinel Event Notification System for Occupational Risk program, but as of the time of this writing is no longer actively funded. Nevertheless, it serves as a role model for state-based surveillance for occupational hearing loss. Case ascertainment was accomplished through reports from employers, audiologists, and otolaryngologists. Workers with identified NIHL were interviewed and industrial hygiene investigations were conducted at companies from which cases were reported but that did not have comprehensive hearing conservation programs in place. The purpose of the program was to prevent additional NIHL by inspecting facilities where cases had been identified. Although Michigan investigators believe that a substantial number of cases may not have been reported, the program has demonstrated that surveillance of occupational hearing loss is feasible. In addition, it has established models for case ascertainment and follow-up activities that could be utilized by other states in developing similar surveillance programs.[133]

Workers' compensation data provide another potential mechanism for surveillance. Daniell and colleagues[134–136] have utilized such records to study trends in the incidence of occupational hearing loss in Washington State. However, the authors believe that compensation claims represent only a fraction of the occupational hearing loss cases, and they note that trends in compensation claims may not be related to trends in underlying disease incidence. Other obstacles in using workers' compensation data for surveillance include significant differences in the availability, quality, and level of detail across states and changes over time in the coding of occupations and injuries.[137,138]

The National Academy of Sciences identified the lack of hearing loss surveillance as one of the major shortcomings of the NIOSH Hearing Loss Research Program. Surveillance data are absolutely essential to progress in occupational hearing loss prevention. Whereas national surveillance systems can be expensive and labor-intensive, considerable valuable data for hearing loss surveillance are already being collected by employers, health professionals, and government agencies. Useful tools are also available, including guidelines specifying the necessary data elements for exposure surveillance[117] and programs for cleaning audiometric data sets.[139]

In 2009, a 4-year National Occupational Research Agenda (NORA)-funded project commenced to develop a national surveillance system for OHL. Relationships were developed within the hearing loss community and audiometric service providers located across the United States were recruited to share their audiometric data with NIOSH. As of 2011, 13 audiometric service providers have been recruited thus far, and over 7.2 million audiograms have been collected. A national repository is being populated as data are received and cleaned.

Data from the collected audiograms will be used to (1) measure the incidence and prevalence of OHL; (2) identify industrial sectors and subsectors with the highest prevalence of OHL; (3) measure the average annual change in hearing ability among workers within industrial sectors and subsectors; (4) identify workplace factors that may be related to OHL (e.g., industry characteristics, geographic region); (5) guide the development of research priorities; and (6) guide workplace interventions to reduce OHL.

Methods for data integration, analysis, and dissemination will improve as the data are utilized. The ability to identify high-risk groups, ascertain additional risk factors, target resources and interventions appropriately, and monitor progress in prevention will lead to a reduction in exposures to hazardous occupational noise and in resulting hearing loss.

RESEARCH NEEDS

- Periodically repeat analyses of established databases (e.g., the BLS survey data, the

OSHA IMIS data, and the NHIS) to identify trends or changes in occupational noise exposure and hearing loss.
- Establish consensus regarding the minimum data elements necessary for effective surveillance.
- Continue systematic yearly collection of audiometric data from audiometric service providers, national repository maintenance, and surveillance activities to identify trends or changes in occupational hearing loss.
- Devise incentives for companies to contribute exposure measurements and audiometric data to a centralized surveillance system.
- Test alternative case-ascertainment systems, such as reporting by audiologists, physicians, occupational health nurses, or workers' compensation programs.
- Develop analysis software to calculate relevant measures of incidence and prevalence of noise exposure and occupational hearing loss from existing data sources.

Mechanisms of Noise-Induced Hearing Loss

Learning Outcomes: As a result of this activity, the participant will be able to describe the physiological basis for noise-induced hearing loss.

The past decade has seen considerable progress in understanding the biological mechanisms underlying NIHL. Original theories regarding the pathophysiology of noise damage assumed that the sensory cells were destroyed by the excessive mechanical vibration created by loud sounds. This view was originally proposed in the seventeenth century (Perrault, 1680 to 1688; cited in Hawkins and Schacht[140]) and has been confirmed by contemporary work as advances in microscopic techniques allowed more detailed examination of damaged cochlear structures.[141] Excessive vibration within the cochlea can detach the organ of Corti from the basilar membrane, destroy hair cells and supporting cells or damage the connections between them, and otherwise compromise the structural integrity of the cochlea. Stereocilia may be damaged, fused, broken, or destroyed or they may become dislodged from the tectorial membrane. Damage to pillar cells can alter the vibratory impedance within the cochlea and lead to a loss of sensitivity. Noise exposure also can disrupt the potassium cycling pathway through the OHCs, endolymph, and stria vascularis that is necessary for normal audition.[142]

Disruption of cochlear blood flow has been implicated in the development of NIHL.[143] The cochlea has a very rich blood supply delivered through the stria vascularis. Noise can cause swelling within this structure, causing the death of intermediate cells and permanently shrinking the stria vascularis, potentially reducing the blood supply to the cochlea.[142] In addition, noise exposure reduces the diameter of blood vessels within the cochlea and slows the velocity of red blood cells. A reduced blood supply disturbs the metabolic homeostasis within the cochlea and can lead to reduced hearing.[143]

Despite increasing knowledge of these mechanical and vascular mechanisms of NIHL in the past decade, gaps remained in our understanding of the pathophysiology of noise damage. Some studies noted significant permanent threshold shifts with little loss of OHCs or disruption of cochlear potentials.[144] The cellular processes underlying alterations of cochlear blood flow were not understood. As early as the 1970s, researchers suggested that metabolic modes of damage might account for the frequent lack of correlation between sensory cell loss and audiometric hearing loss.[145] In the mid-1990s, research implicating reactive oxygen species (ROS) and free radicals in the development of neurodegenerative diseases led investigators to look for similar effects in the auditory system.[146] A free radical is an atom or molecule with a single electron in its outer shell, making it highly reactive with other molecules and potentially destabilizing them. ROS molecules are oxygen-based molecules that are either free radicals themselves or readily able to generate free radicals.[142] ROS are necessary for various cellular processes, but excessive levels of ROS can damage DNA, lipids, and proteins and can lead to cell death.[143] This process is known as *oxidation* and may be slowed or halted through antioxidant mechanisms.

Studies have now clearly confirmed that metabolic damage from free radicals and ROS underlie many of the destructive processes associated with cochlear injury due to noise and other ototoxic exposures. Increased ROS and oxidized lipids and DNA have been found in cochlear tissues following noise exposure. The introduction of ROS generators into the cochlea without noise stimulation has produced anatomic and physiological changes that mimic noise-related damage. Internal antioxidant systems appear to be upregulated following noise exposure, and antioxidant therapies have been shown to be beneficial in reducing cochlear injury following exposure.[146]

The metabolic role of ROS and other free radicals in the development of NIHL may explain the continued loss of cochlear cells following the cessation of exposure. Studies have indicated that loss of OHCs continues for up to 30 days after noise exposure. However, it was previously assumed that all cell death within the cochlea was due to necrosis, in which cells become swollen and eventually rupture in response to serious chemical or physical insult. Necrotic cell death would not explain the continuing damage several weeks postexposure. But metabolic stress that increases ROS within the cell can trigger apoptotic cell death. Apoptosis is a normal, programmed process through which the body eliminates old or unnecessary cells. However, free radical formation following noise exposure can inappropriately initiate apoptotic events. Because apoptosis occurs gradually, this process could account for damage that continues to develop after cessation of exposure.[142]

Although much progress has been made in understanding the processes by which noise damages the ear, there remain many unanswered questions. The cascade of events by which ROS develop in cochlear cells is not clear.[142] In addition, other mechanisms that may contribute to cochlear noise damage are being investigated. Upregulation of genes expressing prestin and β-actin after noise exposure has been reported. These compounds are believed to be necessary for motility of OHCs; upregulation indicates damage to these substances, which could result in loss of hearing sensitivity.[147] Steroid hormones and receptors have been shown to fluctuate in response to noise stress, indicating that the adrenal system also may play a role in regulating the effects of noise on hearing.[148] Multiple, complex pathways of noise damage exist, and there is still much to elucidate regarding them.[142] As basic scientists continue to unravel the underlying mechanisms of NIHL, hearing conservationists should evaluate how this knowledge might be applied to develop more sensitive tests for earlier identification of noise-related changes, which would protect workers before hearing loss occurs.

Another area in which our understanding of noise-related cochlear pathophysiology has been incomplete is in the relationship between temporary and permanent threshold shifts. Although early investigations found a high correlation between TTS and PTS, later studies have shown that the former is not a good predictor of the latter.[149,150] Current research indicates that the histological mechanisms underlying TTS may be different from those that cause permanent loss of hearing. Through a method by which cochleas could be fixed in surviving animals, Nordmann et al[151] investigated TTS and PTS in separate ears of individual animals, which served as their own controls. They reported that ears with TTS showed buckling of pillar cell bodies and decoupling of stereocilia from the tectorial membrane. Ears with PTS showed primarily loss of hair cells and adjacent nerve fibers. The investigators suggested that susceptibility to permanent threshold shifts would be better correlated with repair processes within an individual cochlea than with the magnitude of the preceding TTS. Mulroy and colleagues[152] also concluded that TTS results from reversible changes within the hair cells, distinct from the mechanisms of PTS. They classified TTS-related changes into three categories: those that temporarily decrease the mechanical sensitivity of the stereocilia, those that reduce synaptic transmissions, and those that produce tiny lesions along cell membranes.

Recent work by Kujawa and Liberman[58] in mice showed that complete reversal of TTS, as measured by behavioral thresholds and intact cochlear sensory cells, failed to account for acute loss of afferent nerve terminals and delayed degeneration of the cochlear nerve. These findings question the validity of the traditional assumptions about the relationship of TTS to PTS or even TTS to anatomical damage. They also call into question the assumption that NIHL ceases when exposure ceases. Altogether, they suggest that current practices for monitoring TTS to prevent PTS may be counterproductive, although these practices may still have training value. The uncoupling of the stereocilia from the tectorial membrane and reduction of the mechanical sensitivity of the stereocilia may actually be protective against permanent hearing loss. Early identification and intervention strategies based on the mechanisms specific to PTS and/or neurological damage may be needed.[151]

Finally, the potential interaction between mechanisms underlying NIHL and hearing loss from other causes is still poorly understood. For example, it is unclear whether NIHL and presbycusis are independent processes (and therefore additive) or whether the two processes interact. Data on this question have been conflicting.[149,153] Gates and colleagues[154] found that NIHLs altered the rate of age-related hearing loss in older men who were followed longitudinally in the Framingham Heart Study. They reported that men with greater NIHLs showed slower age-related progression of loss in the notch frequencies and accelerated progression of hearing loss in the lower frequencies, in comparison with men in whom there was little or no evidence of NIHL. In an animal model, Kujawa and Liberman[57] found similar results. However, Boettcher[155] found that age-related hearing loss and NIHL were additive in gerbils and corresponded well to the ISO standard (ISO-1999) describing hearing loss allocation.[37] Previous animal work, however, showed interactions between age and noise such that the ISO-1999 model significantly overpredicted hearing loss due to both noise and age.[156]

A better understanding of the underlying mechanisms by which noise and age damage the ear, independently and collectively, has ramifications for many aspects of hearing conservation. If older workers are more susceptible to the effects of noise, it may be necessary to monitor them more frequently. If NIHL makes workers more susceptible to the effects of age, then they may need audiometric monitoring beyond their working lifetime. If the effects of noise and aging are not additive, then current standards for the allocation of hearing loss may need to be revisited, and current age-correction practices in hearing conservation programs may have validity issues beyond the statistical problem of applying population data to individual workers. Although aging is the most universal hearing loss cause that has the potential to interact with noise, other etiologies (e.g., genetics, ototoxicity) also may warrant investigation.

RESEARCH NEEDS

- Develop more sensitive tests to permit earlier identification of noise-induced damage, based on new knowledge regarding mechanisms of NIHL and neurological effects.
- Reevaluate the utility of midshift audiometric monitoring for TTS as warning signs of imminent PTS.
- Further study the relationship between free radicals and susceptibility to NIHL.
- Clarify the mechanisms and possible interaction by which noise and age affect the auditory system, and evaluate current hearing conservation and workers' compensation practices in light of this possible interaction.
- Investigate other potential interactions between hearing loss from noise and hearing loss from other causes, evaluate their impact on occupational hearing loss prevention efforts, and design new preventive strategies as appropriate.

Factors Influencing Susceptibility

Learning Outcomes: As a result of this activity, the participant will be able to identify the issues associated with individual susceptibility to noise-induced permanent threshold shift.

Although the detrimental effect of noise on hearing is extensive and irrefutable, not all individuals are equally susceptible to NIHL. For example, individuals exposed to 100 dBA for 8 hours a day over a working lifetime could sustain as little as a 30-dB shift or as much as a 56-dB shift in hearing threshold at 4000 Hz.[38] Prevention of NIHL would be facilitated if those individuals who are more susceptible to NIHL could be identified and targeted for special intervention and closer monitoring.

Certain extrinsic factors that influence individual susceptibility to NIHL have been known for some time and are summarized in comprehensive reviews by Humes[157] and Henderson et al[149] (see also "Risk Assessment," (pgs. 150–154) for further discussion of this issue). Males appear to sustain larger noise-induced threshold shifts than females, although it is unclear whether this reflects inherent differences in biological susceptibility or merely gender differences in other lifestyle factors, such as exposure to recreational noise. Age (both young and old) and prior hearing loss can differentially affect noise susceptibility, but findings have been mixed. Race and eye color have generally been shown to correlate with sensitivity to NIHL, with darker pigmentations associated with less NIHL. Even shorter individuals have been shown to have greater susceptibility to NIHL in some circumstances.[158] Taken altogether, however, such biological factors as these appear to account for only a small portion of the variations in sensitivity to noise across individuals.[149]

Physiological correlates of NIHL, primarily within the vascular system, also have been investigated for their utility in identifying individuals who might be more susceptible to noise effects. Vasoconstriction is a narrowing of the blood vessels that results in reduced blood flow and is correlated with noise stress.[159] Interestingly, studies of vasoconstriction as an indicator of NIHL have generally shown a negative correlation between vasoconstriction and measures of threshold shift; that is, individuals with more vasoconstriction exhibit less hearing loss.[159–161] Blood pressure has been examined as a potential correlate with susceptibility to NIHL, but results have been mixed. Dengerink et al[161] found no correlation between systolic or diastolic blood pressure and permanent hearing thresholds, although some measures of TTS were related to blood pressure measures. Thomas and Williams[162] found higher systolic blood pressure among a group of naval aviators who had sustained permanent threshold shifts compared with a group of aviators who had not suffered hearing changes. Two other studies have reported an association between hypertension and NIHL.[163,164] Finally, several studies have consistently shown that measures of overall cardiovascular fitness are positively correlated with protection against NIHL.[161,165,166]

Other research has examined blood serum measures for associations with the development of NIHL. It has been hypothesized that abnormal blood lipid levels accelerate atherosclerotic processes, potentially altering susceptibility to hearing loss specifically from noise. In their study of naval aviators, Thomas and Williams[162] noted a trend toward higher total cholesterol levels in the noise-susceptible group, but it did not reach statistical significance, perhaps because of the small sample size. Pyykko and colleagues[167] found a significant association between cholesterol and NIHL; the effect varied across age categories and was strongest among those aged 40 years and over. Only one study has examined the relationship between high triglycerides and NIHL; it showed a positive trend, but the study was small and the result was not statistically significant.[162] Günther and colleagues[168] noted that magnesium deficiency increases cell membrane permeability, increasing the potassium recycling that occurs during the normal hearing process, possibly leading to cell exhaustion and loss of hearing. They investigated this in a small study of Israeli Air Force pilots and found an inverse relationship between serum magnesium levels and NIHL. However, Walden et al[169] found no association between blood magnesium levels and hearing loss in soldiers exposed to weapons fire. Additional data are needed to clarify any relationship that exists between blood serum measures and susceptibility to NIHL.

As discussed in the previous section on mechanisms of NIHL, the role that ROS play in mediating cell damage and cell death has become increasingly apparent over the past decade. Noise exposure creates free radicals within the cochlear tissues; antioxidants scavenge free radicals and protect the auditory system from damage. Therefore, it could be expected that higher levels of antioxidants would be associated with lower susceptibility to NIHL. This hypothesis has been examined in only one study.[170] No relationship between serum levels of the antioxidant vitamin C and hearing thresholds was observed in 58 noise-exposed factory workers. Unexpectedly, higher levels of vitamin E were significantly associated with poorer hearing in the same workers. The authors suggest that the true effect of vitamin E could have been confounded by age-related hearing loss, as levels of vitamin E are known to be higher in older individuals and vitamin E levels did increase with age in the study sample. Additional studies will be necessary to determine whether serum levels of antioxidants are useful biomarkers for NIHL.

The sequencing of the human genome has opened opportunities to look at the building blocks underlying susceptibility to many conditions, including NIHL. A gene that regulates any part of the auditory process could influence the broad spectrum of variability noted in the effects of noise exposure across individuals. Researchers have begun searching for relevant genes along pathways associated with the cochlear antioxidant system, gap junction channels, potassium ion recycling, and general stress tolerance.

Because noise exposure is known to create free radicals within cochlear cells, it has been hypothesized that genetic aberrations in antioxidant defense systems might increase susceptibility to NIHL. The *GSTM1* and *GSTT1* deletions have been the most studied genotypes in this class; they are present in 25 to 50% of the Caucasian population. Rabinowitz et al[170] found evidence of increased susceptibility to NIHL among factory workers with the null *GSTM1* genotype (i.e., a copy of the *GSTM1* gene that lacks normal function) but not among those with the null *GSTT1* genotype. In a 2005 study of 1261 noise-exposed workers, Carlsson and colleagues[171] found no association between the null genotype of either gene and susceptibility to NIHL, but they found increased susceptibility among smokers who were null for the *GSTM1* gene in a separate study 2 years later.[172] Carlsson also investigated nine SNPs (i.e., single-nucleotide polymorphisms, or DNA sequences) from the *GPX*, *GSR*, and *GSTP1* genes and found no evidence of increased susceptibility.

Other antioxidant enzymes in the cochlea include superoxide dismutase (SOD) and catalase.[171] Genotyping of SNPs relevant to these enzymes has produced mixed results. Fortunato and colleagues[173] reported that SOD2 polymorphisms were associated with increased susceptibility to NIHL among 94 male workers in an aircraft factory. Carlsson et al[171] found no evidence of increased susceptibility to NIHL in CAT1, CAT9, SOD5, and SOD6 with polymerase chain reaction analyses. More recently, Konings et al[174] analyzed SNPs of CAT1 to CAT12 and found that an association between the genes and predisposition to NIHL was evident only in workers exposed to noise levels greater than 92 dB.

Paraoxonases (PONs) also contribute to antioxidant activity in the cochlea. The association between PON polymorphisms and NIHL has been investigated in only one study, which showed that the PON2 C allele was highly associated with NIHL. No significant association was discovered among polymorphisms for PON1.[173] Obviously, more study is necessary before definitive conclusions can be drawn regarding genes regulating antioxidants and susceptibility to NIHL.

Gap junction proteins, which control the transfer of ions and other chemicals between cells in the inner ear, are necessary for cell communication, regulation of fluid balance, and the potassium ion recycling that provides cochlear energy. *GJB2* (connexin 26) is a gene that encodes a gap junction protein; the 35delG mutation in this gene is known to account for more than half of all cases of autosomal-recessive hereditary deafness (the most common type of hereditary hearing loss, in which both parents usually have normal hearing).[175] Several studies have examined this mutation to see if it might also contribute to increased susceptibility to NIHL; however, all of the studies have been negative.[175–177] Van Laer et al[177] also tested SNPs from four other connexin genes (*Cx30*, *Cx30.3*, *Cx31*, and *Cx32*) and again found no association between connexin polymorphisms and NIHL.

Other channels associated with potassium recycling in the cochlea include *KCN* genes and *SLC12A2*. Van Laer et al[177] tested 23 SNPs from these genes in a population of 1261 male, noise-exposed factory workers. Five alleles (different forms of the same gene) and two genotypes of *KCNE1*, *KCNQ1*, and *KCNQ4* were found to be significantly associated with NIHL susceptibility. Statistical significance was lost, however, when a correction factor for multiple testing was applied. Nonetheless, these genes may warrant further investigation.

Heat shock proteins (the hsp70 family) assist with proper protein function in cells when they are exposed to a stressor such as noise. Heat shock proteins can be produced in the cochlea and can be protective against moderately loud sounds, but their expression varies substantially across individuals. Yang et al[178] tested whether polymorphisms in the hsp70 gene family were associated with variations in NIHL in a group of nearly 200 autoworkers in China. They found a slight difference between susceptible and nonsusceptible workers in the B genotype of the hsp70-2 gene, but the difference was not statistically significant.

Although some research has shown associations between certain extrinsic, physiological, or molecular factors and susceptibility to NIHL, it is clear that there is no valid, reliable indicator of susceptibility. Nonetheless, the associations identified should encourage continued study, in an effort to narrow the range of possible susceptibility markers. A simple, valid indicator of NIHL susceptibility could be a useful tool for intervention. However, success in the search for susceptibility markers may be many years in coming.

RESEARCH NEEDS

- Examine identified chemical biomarkers of noise stress (e.g., catecholamines, cortisol, adrenaline, norepinephrine, and salivary chromogranin A) for their utility in identifying NIHL-susceptible individuals.
- Investigate possible effect of lifestyle choices such as diet and exercise on NIHL.
- Investigate genes that are associated with some alteration in the structure or function of the ear in the context of non-noise-related disorders for any correlation with susceptibility to NIHL.
- Validate findings of studies conducted to date, as the paucity of studies on any single factor thus far makes it impossible to draw any conclusions about the potential of a particular susceptibility marker.

Ototoxicity and Combined Effects

Learning Outcomes: As a result of this activity, the participant will be able to identify the nature and consequences of occupational exposure to ototoxicants.

In recent years there has been significant progress in the attempt to understand the effects of noise on hearing when it is combined with other agents in the workplace. This effort includes the study of adverse effects of toxic agents on hearing, even without noise exposure. The neuro-otologic problems associated with agents such as mercury have been known for centuries, but the ototoxicity of industrial chemicals such as toluene and styrene has been identified more recently.[179,180] Toxic chemicals can adversely affect the central nervous system. Some damage the cochlea in much the same manner as noise (although the uptake is through the lungs or skin), but others affect higher sites in the auditory system. With some substances, such as heavy metals or pesticides, hearing loss is less pronounced than other kinds of neurological effects. Solvents like toluene are very common in industry, as are styrene, mercury, and the organotins. Because noise is often present where solvent exposures occur, it can be very difficult to separate the degree of adverse effect caused by each. In addition, mixtures of solvents can cause further difficulties in assessing the harmful effects of single agents.

Morata et al[181] estimated that 10 million U.S. workers are exposed to solvents in the manufacturing industries, many of whom may be exposed to hazardous levels of noise as well. Recent evidence has confirmed that many of these agents are capable of damaging hearing, even without the addition of noise.[182,183] Fechter[183] categorizes industrial ototoxins as shown in Table 4.

Despite the considerable amount of research in this area, criteria supporting dose–response relationships have yet to be developed for most of the studied chemicals. Fechter[183] reported on attempts to develop benchmarks to identify the chemical exposures that can potentiate NIHL. In the meantime, several organizations recommend caution and in some cases are requiring hearing tests whenever workers are exposed to ototoxic chemicals.[28,184–186]

Because chemical exposure can affect several areas of the central nervous system—in contrast to noise, whose main target is the cochlea—researchers have suggested that pure-tone behavioral audiometry may not be a sufficient indicator of damage. For example, toluene, styrene, and xylene may affect the auditory cortex as well as the cochlea; carbon disulfide affects mainly the auditory cortex; and n-hexane affects the auditory nerve.[187] This poses a special challenge to the audiologist. To identify the presence of retrocochlear damage when pure-tone thresholds are within normal limits, procedures such as filtered speech, random gap detection, pitch pattern sequence, and dichotic digits could be used to assess central auditory processing function in cases of chemical or noise-plus-chemical exposures.[188,189]

Two conferences held in recent years brought together experts from around the world to share their research. The NIOSH Best Practices Workshop: Combined Effects of Chemicals and Noise on Hearing was held in Cincinnati in 2002, and the international

Table 4 Industrial Agents That Are Considered Ototoxic, as Categorized by Fechter[183]

Organic Solvents	Metals	Asphyxiants	Endocrine Disrupters
Toluene	Mercury	Carbon monoxide	Aroclor 1254
Styrene	Lead	Hydrogen cyanide	Acrylonitrile
Ethylbenzene	Trimethyltin		
Xylene			
Trichlorethylene			

symposium Health Effects of Exposure to Noise and Chemicals, sponsored by the Nofer Institute of Occupational Medicine, took place in Poland in 2006. Presentation topics included the pathophysiology of noise-induced and solvent-induced hearing loss, peripheral and central auditory effects, vestibular effects, and the outlook for health and safety standards. Summaries of these conferences are available in works by Morata[182] and Sliwinska-Kowalska et al.[190]

The interaction between noise and chemicals has been the subject of successful international cooperation in recent years, leading to the formation of a subgroup funded by the European Commission called *NoiseChem*, consisting of 10 experts in hearing and toxicology. The subgroup's final report, entitled *Noise and Industrial Chemicals: Interaction Effects on Hearing and Balance*, was issued in 2004 and includes this summary of the main findings from occupational studies[191]:

- Human studies suggest that solvents are ototoxic.
- Exposure to industrial solvents can cause permanent hearing loss, both peripheral and central, though results vary.
- Hearing loss can occur at exposure levels within permitted occupational exposure limits.
- There is evidence of a dose–response relationship between hearing thresholds and levels of exposure.
- A synergistic effect of combined noise and solvent exposure, even at levels below permitted occupational exposure limits, has been noted, though results vary.
- It is very difficult to separate out the individual effects in combined exposures.
- Minimal effects are often noted on pure-tone audiometric thresholds.
- Pure-tone audiometric results can indicate a high-frequency loss or a hearing loss that affects a wider range of frequencies.
- The indications are that hearing loss occurs earlier and is more serious among workers exposed to carbon disulfide and noise.
- Effects of solvents continue after exposure ceases.
- Exposure to solvents can result in central nervous system disturbance.
- Exposure to solvents can result in balance abnormalities.
- Exposure to solvents can result in vestibular disturbance. Long-term exposure can cause cerebellar lesions, as indicated by decreased vestibulo-ocular reflex suppression (VORS), pathological spontaneous and positional nystagmus, pathological increased saccade speed, and abnormal gain in smooth pursuit.
- Vestibulo-oculomotor testing is valuable in testing central nervous system lesions in solvent-exposed workers.
- Study parameters vary, often making it difficult to compare results.

The Nordic Expert Group for Criteria Documentation of Health Risks from Chemicals recently published *Occupational Exposure to Chemicals and Hearing Impairment*, which not only reviews studies to date but also presents evaluations of human health risks, groups at extra risk, and recommendations by international bodies.[192] This document also includes a discussion of an innovative proposal by Hoet and Lison,[193] who suggest the adoption of a "noise notation," a concept inspired by the widely used "skin notation." Skin notation criteria were introduced almost 50 years ago as a qualitative indicator of hazards related to dermal absorption at work. Such noise notations could be used in the identification of ototoxic chemicals and prompt specific preventive measurements, including targeted medical surveillance. (For further information on the Nordic Expert Group's recommendations, see www.nordicexpertgroup.org.)

Although there is effective international cooperation in research in this area, the results do not appear to be sufficiently available to those involved with protecting workers' hearing in the workplace. Better coordination is needed among researchers and practitioners in audiology, industrial hygiene, and toxicology for the mitigation of hearing loss due to exposure to ototoxic agents and to these agents in combination with noise.

RESEARCH NEEDS

- Improve the testing of chemicals to properly evaluate their ototoxicity.

- Conduct multidisciplinary epidemiological investigations that include mixed-exposure assessment.
- Identify the levels of noise and chemicals, separately and in combination, that can be considered safe to the human auditory system.
- Develop dose–response relationships to be used for damage-risk criteria and recommended exposure levels for ototoxins and toxin-plus-noise conditions.
- Determine the mechanisms of toxicant-induced and toxicant-plus-noise-induced hearing loss.
- Develop demonstration hearing conservation programs for workers exposed to ototoxic agents, with an emphasis on industrial solvent exposure.

Consequences of Occupational Hearing Loss

Learning Outcomes: As a result of this activity, the participant will be able to discuss the consequences of occupational hearing loss.

Professionals in occupational health, audiology, and medicine tend to forget that individuals with NIHL, like any sensorineural hearing impairment, have a greater handicap than one might think at the first encounter. In fact, there is a tendency to discount hearing loss as an inevitable consequence of a noisy occupation, even today, after more than 35 years of a federal noise standard and 25 years of detailed requirements for hearing conservation programs in general industry. When hearing-impaired people are queried closely, as well as (and especially) their spouses, the nature of the handicap can be seen as more serious, which gives impetus to the need for prevention.

People often think that hearing impairment from noise is a problem only in the later years of life, but the truth is that it affects people all through their work life. Even before a hearing loss becomes permanent, temporary hearing loss occurs. Workers may come home with a hearing impairment that affects their family life, even if their hearing returns to normal during the night. They may have difficulty communicating with their spouse or children or with hearing the radio or television. In addition, when they arrive home, they may need a quiet period because of fatigue and nervousness caused by the noise at work. Then, as permanent hearing impairment builds up, it is overlaid by temporary hearing impairment, which makes the handicap more severe. Workers exposed to high levels of occupational noise will tend to incur most of their hearing loss within the first 10 to 15 years of exposure, but of course the progression of hearing loss is dependent upon the exposure level (see ANSI S3.44–1996, R 2001[38]), as well as individual factors. Although the loss will progress with the aging process, it may begin at a relatively young age.

The impact of noise-induced hearing impairment and the resulting handicap may be experienced in several areas of a person's life: (1) safety and communication at work, (2) social interaction and communication at home with family and friends, (3) self-esteem, and (4) ability to relate to sounds in one's environment. The difficulties in these areas may apply to all levels of hearing handicap, even mild impairments. The degree of difficulty is only somewhat dependent upon the degree of handicap as measured by pure-tone hearing threshold levels.

Pioneering research on the impact of NIHL has been conducted by Hétu, Getty, and their colleagues, and it involved Canadian workers.[194–198] The results of their studies elucidated the stigma of NIHL, evidenced by the reluctance of workers to acknowledge difficulties, the psychosocial disadvantages experienced in social and family life, and the impact of hearing loss on intimate relationships. They indicate that hearing rehabilitation programs for workers with NIHL would be helpful, although such programs are rare. (See further discussions in Part 2, "Treatment and Rehabilitation" (pgs. 235–237) in the next section, "Addressing the Problem.")

More recently, a comprehensive study of the effects of NIHL at work was performed by Morata and coworkers at NIOSH.[199] The study involved collecting information from 31 workers with self-reported noise exposure and hearing loss, along with eight supervisors and program managers, through a series of focus groups. The results showed serious concerns about job safety; ability to hear communication and warning signals, especially when using HPDs; ability to monitor the sounds of machinery and other environmental sounds; future quality of life; and future employability. Similar perceptions were voiced by supervisors and, to a lesser extent, by hearing conservation program managers.

Figure 1, from Morata et al,[199] shows the substantial number of workers expressing concerns about various workplace issues relating to their noise exposures and hearing losses. The adverse effects of HPDs on

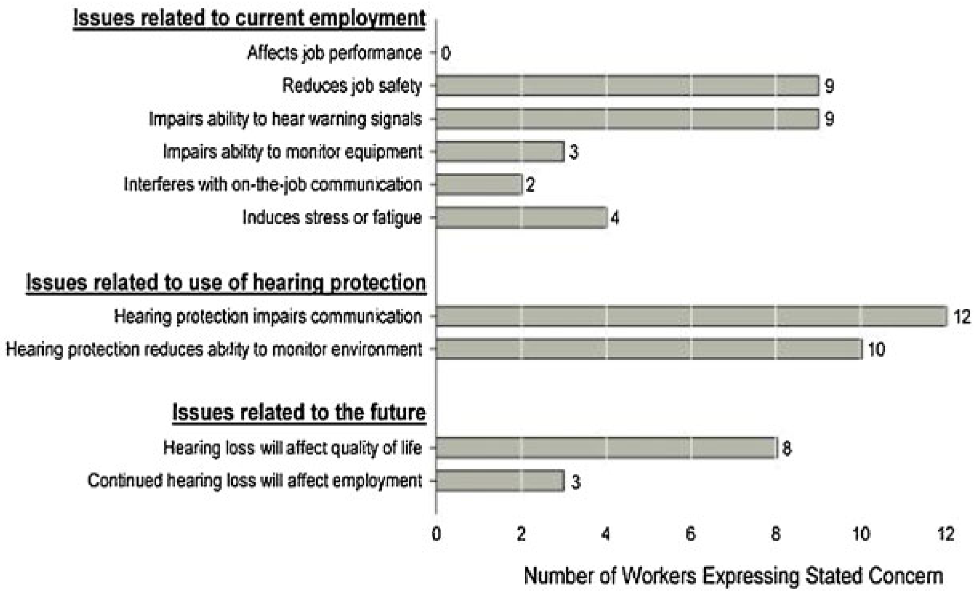

Figure 1 Difficulties and concerns expressed by noise-exposed, hearing-impaired workers and frequency of their expression during focus group sessions (reprinted from Morata et al[199]). There were a total of 31 workers in the focus groups.

communication and on the ability to monitor the environment were among the top concerns, as were safety and the ability to hear warning signals. Workers frequently stated that they had to remove HPDs to communicate, which would exacerbate the risk of hearing loss. The hearing-impaired workers also described some of the features that would comprise the ideal workplace for their handicap. These included well-maintained equipment; baffles or enclosures on the noisiest machinery; custom-made ear plugs; a "caring" work environment where management is truly interested in employees and the workplace issues that affect them; a high-quality public address system; lights to indicate start-up of noisy equipment; and quiet areas around the shop floor.

The investigators point out that conventional hearing conservation programs do not distinguish between workers with normal versus impaired hearing. Additionally, other than giving a nod to the concept of making a reasonable accommodation, governmental regulations and professional organizations have yet to address specific policies for workers with NIHL.[199]

RESEARCH NEEDS

- Gather information on the prevalence of currently employed workers with NIHL and the severity of impairments.
- Design training programs for supervisors and hearing conservation program managers on the special needs of hearing-impaired workers.
- Examine the impact of hearing impairment on the audibility of warning sounds and other environmental sounds necessary for safety and productivity.
- Develop a standard evaluation and intervention technique that will provide supervisors and hearing conservation professionals with tools to ensure the safety and hearing health of workers with NIHL.
- Investigate the appropriate use of HPDs versus hearing aids in the work environment.

Economic Impact of Occupational Hearing Loss

Learning Outcomes: As a result of this activity, the participant will be able to describe the economic burden associated with occupational hearing loss, as well as methods for and limitations associated with estimating the economic impact of occupational hearing loss.

In addition to the significant personal, social, and occupational impact of hearing loss and other adverse effects of noise on individual workers that have been discussed in previous sections, noise exposure and occupational hearing loss have substantial consequences for society as a whole. These consequences include the economic costs associated with diagnosis, treatment, rehabilitation, and compensation of affected workers and the social costs of disease burden reflected by reduced quality of life, disability, and suffering.[200,201] They also include other costs of noise exposure, such as accidents and absenteeism.

Few studies have examined the socioeconomic impact of work-related NIHL. Two recent reviews estimated the costs of all hearing loss in the general population in Australia[201] and the European Union[202] but did not specifically examine the costs of occupational hearing loss. The total financial burden of hearing loss from all causes (including both direct health expenditures and indirect costs such as lost earnings and welfare payments) was estimated to be $11.75 billion (AUS) in Australia in 2005, representing 1.4% of the gross domestic product.[201] Shield[202] estimated the overall cost of hearing loss in the European Union (including both economic and social costs) to be €224 billion euro in 2004. Ruben[203] constructed estimates of the economic costs of all communication disorders in the United States, not including the social costs of disability. He reported economic costs between $154 billion and $186 billion per year, representing 2 to 3% of the gross national product. Although these reviews provide little information regarding the specific costs of occupational hearing loss, they provide useful frameworks for conducting similar analyses of work-related NIHL.

The most common measure of the economic costs specifically related to occupational hearing loss is the amount of compensatory damages paid to affected workers. However, even this measure is difficult to estimate. There is wide variation in how occupational hearing loss is compensated, both within the United States and across other nations.[204] In the United States, each of the 50 states and 4 territories as well as 3 federal systems administer unique workers' compensation programs for hearing loss that vary in their definition of handicap; schedule of benefits; adjustment for preexisting hearing loss, presbycusis, or failure to use hearing protection; and other important factors.[205] A few isolated estimates of the compensatory costs of NIHL have been published. In Oregon, workers' compensation claims for NIHL totaled nearly $6.9 million between 1984 and 1998, with an average settlement of just over $5000.[206] Daniell et al[134,135] reported that total workers' compensation costs for occupational hearing loss in Washington State were $4.8 million in 1991 alone. These costs include only disability settlements and do not reflect medical costs associated with diagnosis and treatment. On the basis of this estimate, NIOSH calculated that disability costs for NIHL across the entire United States would exceed $242 million per year.[207] Daniell and colleagues[136] repeated their analysis of Washington State claims data for occupational hearing loss through 1998 and reported that total compensatory costs for work-related hearing loss were $45.7 million that year, with an average settlement of $7180 per worker.

Because workers' compensation awards are based on an historic compromise between labor and management,[208] they represent the low end of the valuation of human hearing. Awards resulting from civil suits, the schedules used by the U.S. Veterans Administration and the U.S. Department of Labor for federal employees, as well as other types of valuations result in considerably higher estimates. The U.S. Veterans Administration reported compensation costs for service-connected hearing loss and tinnitus exceeding $1.2 billion in fiscal year

2006; an additional $288 million is spent annually on hearing aids and audiological services for affected veterans.[209]

The economic costs of occupational NIHL are high in other areas of the world as well. The Accident Compensation Corporation in New Zealand reported total costs of over $53 million during the 2005 to 2006 financial year, a figure that includes disability payments and rehabilitation costs.[210] The Workers' Compensation Board of Alberta, Canada, estimated an average cost per claim exceeding $14,000 in 1983, including compensation payments and administrative costs. Applying this figure to the trend in claims rate for NIHL, Alberta officials estimated that NIHL would cost the province over $5 million in 1987.[200]

Compensation costs for NIHL are high not only in terms of absolute expenditures but also relative to other compensatory occupational illnesses and injuries. The U.S. Veterans Administration reports that in the United States, hearing loss and tinnitus are the two most common disabilities related to military service; over 444,000 veterans currently receive benefits for hearing impairment, and more than 395,000 are being compensated for tinnitus.[209] Fausti et al[211] report that the Veterans Administration paid $1.2 billion in the combined fiscal years 2005 and 2006 for service-related hearing loss and tinnitus. A European study of the economic costs of various occupational diseases, based on national insurance data, revealed that compensation costs for NIHL accounted for an average of 10.3% of the total cost of compensation between 1999 and 2001, ranking third after asbestos-related diseases and musculoskeletal disorders. Percentages of costs by individual country ranged from 0.5% in France, where the only costs associated with NIHL are a pension (usually granted late in life), to nearly 30% in Italy, where a previous lack of clear diagnostic criteria has led to generous though disparate payouts in various regions of the country.[212]

Despite the paucity of consistent data regarding the economic burden of NIHL, the costs are indisputably high.[210] Furthermore, the costs generally appear to be increasing. McCall and Horwitz[206] reported that the average cost per claim for NIHL in Oregon increased from $3699 between 1984 and 1989 to $6705 between 1990 and 1998. In Washington State, Daniell and colleagues[136] reported a nearly 12-fold increase in the number of accepted claims for occupational hearing loss between 1987 and 1998, despite an overall decline in workers' compensation claims for all conditions over the same period. Alleyne and colleagues[200] reported that the number of claims for NIHL submitted in Alberta, Canada, increased an average of 20% annually between 1979 and 1983. A similar 20% annual increase rate in New Zealand in the decade of 1995 to 2006 was reported by Thorne et al.[210]

Understanding the economic costs of NIHL, as well as the benefits of prevention, has utility beyond merely accounting. Models of costs and benefits can be useful in acquiring the necessary resources to invest in preventive activities and to properly allocate funds. For example, Bertsche et al[204] evaluated the costs and benefits of a company's hearing conservation program. The detailed assessment of costs associated with the program included the number of employees enrolled in the program; their hourly wage; the time they spent away from work to be tested, counseled, and trained; the time invested by the occupational health nurse administering the program and the nurse's hourly wage; the cost of training the nurse to manage the program; the time and fees associated with the contract physician and audiologist; the cost of equipment and calibration; and the annual cost of space in the health clinic dedicated to the hearing conservation program. The average annual cost of administering the program between 2001 and 2004 was $19,500, or approximately $50 per employee. On the basis of costs per claim for work-related hearing loss reported by other studies, the authors concluded that preventing one to four cases of NIHL per year would make the program cost-effective. These costs may be somewhat low. More than 25 years ago, OSHA estimated $53 per worker per year, or a total of $270 million per year for the 5.1 million workers exposed to noise at levels of 85 dBA and above.[6]

Sachs and colleagues[213] developed a model for estimating life-cycle costs associated with noise exposure and hearing loss among U.S. Navy machinists. The model incorporated hearing conservation program costs, medical costs, disability compensation, and overhead incurred over the lifetime of the sailors, including both active duty and retirement. The model has certain limitations in that it is based on a captive population (Navy personnel) exposed only to steady-state noise in a specific exposure pattern and does not include compensation costs for tinnitus. However, it could be modified and extended to other types of employment, and it could be a useful tool in cost-benefit analyses.

Economic costs, however, are not the only costs borne by society as the result of occupational hearing loss. In fact, some would argue that the financial burden is not even the most significant. Ruttenberg[214] points out that some dictionary definitions of cost focus on pain, suffering, sacrifice, and distress rather than monetary outlay. Similarly, dictionaries define benefit in terms of value and welfare rather than financial savings. To understand the true costs of occupational NIHL and the benefits of prevention, the full range of costs and benefits must be presented. These include long-term costs and benefits (beyond the quarterly or annual accounting summary), indirect costs and benefits (such as loss of income or reduced absenteeism), positive and negative secondary effects (such as extended equipment life or creation of new markets), and quality-of-life issues. Few studies of the socioeconomic impact of occupational NIHL have included these measures.

A long-standing problem in the analysis of the economic consequences of hazardous noise exposure is the compartmentalization of expenses and savings. Quite often, the department that pays for noise reduction, hearing protection, and other activities geared toward reducing work-related hearing loss is separate from the department that must pay out compensation benefits to workers who sustain such a hearing loss. In this situation, the department that pays for the preventive services never sees any return on its investment. Another problem is that cases of NIHL that are averted are difficult to enumerate. The department paying compensation costs is unaware of the savings that it may be reaping.[214] Methods to estimate these long-term costs and benefits in a more global way could encourage investment in hearing loss prevention beyond mere regulatory compliance.

Indirect costs and benefits are also often overlooked in estimating the socioeconomic impact of noise at work. Indirect financial costs associated with noise exposure and the resulting hearing loss include absenteeism, reduced earnings, lost tax revenues, welfare payments, and vocational rehabilitation programs.[201] Very few estimates of the indirect costs of NIHL are available, but evidence indicates that they may be substantial. The economic basis of many developed countries has shifted from manual labor to communication, and fitness for work now depends largely on a person's communication abilities.[203] According to Ruben,[203] average income among hearing-impaired workers is less than half the average income of the population with normal hearing. By contrast, income among persons with disabilities of any kind is only 15% lower than that in the nondisabled population. The loss of income from underemployment is estimated to be over $21,000 per year per hearing-impaired person.[203] In Australia, hearing-impaired individuals are 25% less likely to earn high incomes than persons with normal hearing.[201] Although estimates are lacking for loss of income specifically among workers with noise-induced hearing impairment, figures regarding the hearing-impaired population overall indicate the need to evaluate such indirect economic costs among the occupationally hearing-impaired workforce.

A study of workers in a boiler manufacturing plant before and after implementation of a hearing conservation program pointed to an indirect benefit of hearing conservation programs. Absenteeism was reduced by 50% after the hearing conservation program was introduced.[215] Methods of evaluating the impact and prevention of occupational hearing loss on indirect benefits as well as costs are needed to better estimate the true economic impact of NIHL and hearing conservation efforts.

In its economic analysis to support the Hearing Conservation Amendment, OSHA estimated the costs and benefits of compliance with the new regulation.[6] On the basis of studies and other evidence submitted to the hearing record, the agency attempted to quantify benefits from the implementation of hearing conservation programs such as improved workplace safety, reduced absenteeism, and reduced workers' compensation payments. From studying the effects of noise on safety and the resulting lost workdays, the agency estimated 362,000 lost-workday cases from exposure to 85 to 90 dBA and 477,000 lost-workday cases from exposure above 90 dBA. The cost of lost productivity for each lost-workday case was approximately $14,000. From the evidence on the effects of noise on absenteeism, OSHA estimated 1 additional absent day per worker exposed above 85 dBA, at a value to industry of $400 million per year. Although ~70% of the workers at that time lived in states with little or no workers' compensation for hearing loss, OSHA estimated the potential savings from workers' compensation costs for workers exposed to 85 dBA or above to be about $530 million over a working lifetime (40 years). According to OSHA, "workers' compensation payments are transfer payments from employers to impaired workers. The true social cost is the incidence of occupational hearing impairment and the various other ill effects of noise; the true social benefit is the reduction in the number of hearing impairments and ill effects."[6(p.4116)] Benefits from noise reduction that the agency recognized but was unable to quantify were the extra-auditory health benefits, reduced medical costs, decreased annoyance or aversion to noise and to the use of HPDs, and improved worker productivity.

Protecting workers' hearing can have other benefits, beyond those for the individual worker, that should be factored into cost-benefit analyses. For example, Ruttenberg[214] cites examples of simple noise control measures that not only reduced worker exposures but also extended the life of the equipment by reducing vibration. This type of secondary advantage should be figured into a company's analysis of the benefits obtained from its noise control investment. In a wider sense, noise reduction and hearing conservation do not affect only the individual company that implements these programs. New businesses are created to meet evolving safety needs, stimulating economic growth in the broader community.[214] Development of new technologies may find applications beyond noise control. Scientific advances could generate public attention, resulting in awareness of noise hazards outside the workplace and an overall reduction in hearing loss. On the negative side, payment of unnecessary compensatory damages can stifle a company's competitiveness, reducing employment and removing wealth from the community.[216]

Perhaps most importantly, the impact of NIHL on quality-of-life measures needs to be included in assessments of the socioeconomic consequences of occupational hearing loss. This requires converting measures of functional hearing impairment to units that can be equated across other impairments, as well as potentially assigning monetary values to allow comparison with other costs. Although some may feel an aversion toward placing a value on the loss of hearing, a function which is both invaluable and irreplaceable, failure to account for the societal consequences of NIHL artificially reduces any evaluation of both its absolute cost and its relative impact in comparison with other disabilities.

Several general methods for measuring disease burden have been applied to hearing loss.

One measure common in health economics is the quality-adjusted life-year (QALY). The QALY methods assign a monetary value to 1 year of life with full quality and then adjust the change in quality by a factor reflecting the degree of the health effect. Because QALYs have an associated monetary value, they can be used in cost-benefit comparisons of various interventions and disabilities. For example, the Cost Utility Ratio reflects the ratio between the cost of an intervention and the change in QALYs resulting from the intervention. Results of this approach are highly dependent on the monetary value assigned to one QALY, as well as the assigned adjustment factors for various degrees of hearing loss. Adjustment factors that have been used for hearing loss range from 0.8 to 0.975 for mild hearing loss, 0.7 to 0.9 for moderate hearing loss, and 0.6 for profound hearing loss. Obviously, the choice of adjustment factors and the value assigned to one QALY can significantly affect the calculated socioeconomic costs of the disability.[202]

The Health and Safety Executive in the United Kingdom recently utilized the QALY approach to calculate the effect of stricter hearing protection regulations on lifetime costs of occupational hearing loss. The organization calculated that a 30-dB hearing loss would cost £48,000 over an individual's working lifetime and a 50-dB hearing loss would cost £96,000. The Health and Safety Executive was able to construct a cost-benefit ratio based on these figures to evaluate the effect of changing the regulations. However, both the adjustment factors and the value assigned to a single QALY were much lower than those used in other studies reviewed by Shield,[202] highlighting the impact which assigning these values can have on calculated costs.

Disability-adjusted life-years (DALYs) are another approach to measuring disease burden. Conceptually, a DALY is the opposite of a QALY; whereas QALYs measure quality of life (where a value of 1 is equivalent to perfect health), DALYs measure disability (where 0 is equivalent to perfect health and 1 is equivalent to death). Originally developed by the World Health Organization, DALYs incorporate the effects of premature death as well as reduced quality of life into a single metric and have operationalized definitions intended to reduce variability across persons and countries.[201,217,218] Nelson and colleagues[219] utilized the DALY approach to estimate the global burden of occupational NIHL. They reported that work-related hearing loss accounted for over 4 million DALYs worldwide in the year 2000. Although most of this burden was carried by developing countries, occupational hearing loss was responsible for 123,000 DALYs in the United States in that year.

The disadvantage to the DALY approach is that it is not framed in economic terms, making it difficult to utilize in cost assessments. A monetary value can be placed on a single DALY to overcome this problem, but determining the appropriate value is no easier than with the QALY approach. Values for 1 year of complete disability ranging from $60,000 (AUS) to $175,000 (U.S.) have been proposed.[201] Again, the value used will significantly affect the estimated socioeconomic impact of NIHL.

The contingent valuation method is another approach that has been used by health economists to assign monetary equivalents to quality-of-life issues. In this method, individuals are asked to determine the amount they would be willing to pay for a particular health benefit or, conversely, the amount they would be willing to accept to forego that benefit. This approach avoids arbitrary assignation of monetary values to such intangible costs as health and disability. However, there is wide variation in the methods used across studies, including differences in survey format, question structure, and selection of target populations and sampling frames. Results of such studies are highly dependent on the types and structure of the survey questions, resulting in issues of generalizability.[204,220]

A Dutch study by Ferrer-i-Carbonell and van Praag[221] utilized a variation of the willing-to-pay approach to determine the income change individuals consider equivalent to the loss of life satisfaction associated with various illnesses or disabilities. Subjects were asked to define the monetary amount they would be willing to pay to avoid a particular condition. Results indicated that on average, workers would be willing to forego 20% of their income to avoid hearing loss. Replications of this study would be needed to verify the consistency with which various populations value hearing ability. The method could also be used to evaluate what workers would be willing to pay to avoid wearing hearing protectors and to avoid the noxiousness of noise.

Ruttenberg[214] suggested a more global method of evaluating the costs and benefits associated with health outcomes. Drawing on the concept of natural resource damage assessments, which are increasingly used to evaluate the impact of various projects on natural resources, she proposed development of "human resource damage assessments" to evaluate the effect of various exposures and outcomes on the "unique and irreplaceable assets" of workers. Shifting the focus from lost workdays or reduced productivity to qualities such as hearing ability might increase incentives for worker protections.

Efforts to date to quantify the socioeconomic effects of work-related hearing loss serve to highlight the gaps that still need to be addressed. Furthermore, the accuracy of existing estimates may be questionable for several reasons. First, valid estimates rely on sound epidemiological data on the incidence and prevalence of noise exposure and associated impairments, which—as noted earlier in the "Surveillance" section (pgs. 161–164)—are lacking.[210] For example, Franks[222] noted that a 12% discrepancy between two estimates of the number of noise-exposed workers resulted in a difference of more than $94 million in the estimated cost of implementing hearing conservation programs in the United States. Second, the criteria used to define occupational hearing loss are inadequate for characterizing the extent of the disability sustained. Pure-tone air conduction thresholds do not capture the degree of functional impairment sustained by workers, particularly regarding communication difficulties and adverse listening conditions.[210] Finally, many studies have provided point-in-time estimates that may be outdated even at the time they are published. Ongoing monitoring of the economic and social consequences of occupational hearing loss would serve to increase awareness of the high costs of this preventable condition.

RESEARCH NEEDS

- Develop consistent, comprehensive models for measuring the direct and indirect costs of noise exposure, occupational hearing loss, and preventive programs.
- Identify and evaluate the benefits of noise control and hearing conservation that extend beyond the narrow realm of hearing ability, including productivity, the ability to hear communication and warning signals, and the prevention of accidents, absenteeism, aversive responses, and adverse health effects.
- Design methods of assessing the value of normal hearing and the impact of hearing impairment on quality-of-life issues such as stigma, stress, socioeconomic status, social isolation, perceived disability, and related factors.

Communication, Safety, and Warning Signal Interference

Learning Outcomes: As a result of this activity, the participant will be able to discuss how hearing loss and hearing protector use are related to worker safety as well as to a worker's ability to communicate and hear warning sounds.

The idea that noise can interfere with or mask speech communication and warning signals would seem to be common sense. Although some industrial processes can be performed with a minimum of communication among workers, other jobs, such as those performed by airline pilots, railroad engineers, and military vehicle commanders, rely heavily on speech communication, auditory monitoring of the equipment or environment, and identification of warning signals.

People have learned from experience that in noise levels above ~80 dBA they have to speak loudly, and in levels above 85 dBA they have to shout. In levels much above 95 dBA they have to move very close together to communicate at all. Although there are methods to predict the amount of communication that can take place in industrial situations, contingent upon various characteristics of the noise and the distance between talker and listener, these methods are rarely employed. One reason is, of course, that the use of HPDs is mandatory in TWA levels above 90 dBA and advised above 85 dBA, and the acoustical characteristics in the listener's environment are thereby changed.* We need practical methods to account for the effects of HPDs on the acoustical environment and any necessary communication or warnings.

It is also common sense that noise can interfere with safety, and although it is a difficult and complex area in which to obtain data, researchers are becoming increasingly attentive to this problem. For example, despite the lack of conclusive data, reports of occurrences suggest that high noise levels and the high incidence of accidents and fatalities in construction are most likely related. Studies have implicated noise and hearing loss in a large percentage of the injuries among shipyard workers[223] and other workers, such as equipment operators and laborers.[224] There have also been numerous anecdotal reports of workers whose clothing or hands have become caught in machines and who have been seriously injured while their coworkers were oblivious to their cries for help. Morata et al[199] noted that noise-exposed workers who had a hearing loss perceived themselves to be at risk for accidents on the job. Another study of workers' beliefs and attitudes revealed that 55% of the noise-exposed workers surveyed indicated that they could not hear warning signals when using HPDs.[225]

Related studies are described in the literature by Choi et al,[226] who found that hearing loss and the occasional use of hearing protectors were significantly associated with the risk of injury among agricultural workers. In addition, Viljoen et al[227] found that hearing loss did not appear to increase the safety risk for coal miners older than 29 years, but it did increase the risk for younger workers.

Recent research by a Canadian team investigated the relationship between workplace accidents, noise, and hearing loss.[228,229] The results have important implications for safety in the manufacturing industries. They found that, when controlling for age and noise exposure, even a mild hearing loss corresponded to an increased risk of accidents (relative risk, 1.14) and that overall, 12.2% of the accidents were attributed to a combination of noise exposure and NIHL.[228] The relative risk of multiple accidents is approximately three times higher among severely hearing-impaired workers (>51-dB HTL averaged over 3, 4, and 6 kHz) when they are exposed to high noise levels (>90 dBA).[229] Similar results have been found by Brazilian researchers,[230,231] although the degree to which these studies controlled for the danger inherent in high-noise-level jobs is unclear.

Researchers at Michigan State University and Wayne State University created an

* *Although the regulatory requirement is based on the TWA, it is more convenient for employers to use actual noise levels in noisy areas for recommending or requiring HPDs.*

epidemiological surveillance system for workplace fatalities, of which one purpose is to assess the role of noise and hearing impairment in the identified fatalities.[232] The research team noted that being struck by an object or caught or compressed by equipment or collapsing material accounted for 20% of the fatalities and is the second leading type of fatal events in Michigan, where noisy manufacturing is a common type of workplace. They also note that several studies suggest a relationship between noise and fatalities as well as hearing impairment due to injuries in the workplace. However, in Michigan, as elsewhere in the United States, OSHA inspections following workplace fatalities do not involve an investigation of the role of noise as a contributing factor.

In a nested case–control study of male Brazilian steel workers, Barreto et al[233] found that impaired hearing and noise exposure were positively correlated with motor vehicle fatalities off the job and that odds ratios increased with higher exposures. The authors suggest that in addition to the obvious difficulties caused by hearing loss, workers who are constantly exposed to noise may be less attentive to both sound and vehicle velocity when off the job.[233] Adverse aftereffects from noise exposure have been well documented in several investigations, particularly with respect to tasks that are sensitive to frustration intolerance (see Chapter 4 in Suter[234]).

Much useful information about the effects of industrial noise on workers has been gathered through the large study known as the CORDIS.[235] Whereas most of the extra-auditory effects will be discussed in the "Extra-Auditory Effects of Noise Exposure" section (pgs. 193–195), the findings related to accidents are relevant here. Some 2368 workers from industries such as textiles, metalworking, and food products were divided into noise exposure categories of low (<75 dBA), moderate (75 to 84 dBA), and high ($\geq$ 85 dBA). The authors found that higher noise levels were associated with increased accidents and absences for both male and female workers and that accidents increased by nearly 50% for both sexes at high versus low noise levels.

These types of studies point to a serious need for a systematic study of the contribution of noise and hearing impairment to workplace accidents, injuries, and fatalities. The cost of these occurrences must be assessed in terms of not only human lives and suffering but also workplace efficiency and economy.

There have been attempts to increase the worker's ability to hear and understand auditory warning signals through technology. For example, backup alarms have been developed that monitor ambient sound levels and can automatically adjust to maintain an audible output in a range of environments (Star Warning Systems[9]). Laroche and her colleagues have worked for several years to develop a model that estimates the optimal level and spectrum of warning signals for specific workplaces.[236,237] The most recent version of Detectsound, a computer model developed by the Groupe d'Acoustique de l'Université de Montréal, takes into account the hearing threshold levels of workers and the attenuation provided by HPDs, as well as the characteristics of the workplace noise.[238]

Another problem that is increasingly recognized by professionals in hearing conservation and occupational safety is that HPDs may interfere with the perception of speech and warning signals. This appears to be true mainly when the wearers already have hearing loss and/or the noise levels fall below 90 dBA. Over the past several decades there has been considerable work in this area, especially by Noble and colleagues in Australia.[239–242] Studies show that HPDs can actually improve speech communication in high background noise levels (i.e., when levels exceed ~90 dBA), when the listener has normal hearing, and especially when the HPD provides relatively flat attenuation across frequencies. They also show, however, that HPDs usually have an adverse effect on speech communication when the listener's hearing threshold levels exceed an average of ~30 dB at 2000-, 3000-, and 4000-Hz frequencies or when the environmental noise levels fall below ~85 dBA. The attenuation of HPDs can also facilitate the perception of a warning signal by taking the signal out of the range of distortion, but this advantage is contingent upon normal hearing, high noise levels, and simple detection paradigms. Sound localization can be adversely affected, particularly in the case of earmuffs.[234,243] A study of sound source identification with use of earmuffs led Abel and Shelly Paik[244] to conclude that "earmuffs should not be used in situations where the perception of the direction of hazard is a concern." These investigations examined the effects of active noise reduction devices as well as passive attenuators and found that the active noise reduction devices did not further degrade directional hearing.

Several recently published studies have explored these issues further. One investigation revealed that with normal-hearing listeners, ear plugs tended to enhance the perception of a warning signal, whereas earmuffs did not. However, as subjects' hearing threshold levels exceeded an average of 20 dB at 500, 1000, and 2000 Hz, their ability to detect the warning signals deteriorated with either plugs or muffs, in comparison with no protection.[245] Council Directive 89/656/EEC of the European Union requires employers to perform an assessment of personal protective equipment and the risks that it may introduce. Further information is given in European Standard EN 458 (1993) on hearing protectors and European Standard EN 457 (1992) on auditory danger signals.[246] Toppila et al[247] also discussed various ISO standards and EN directives pertaining to noise, hearing loss, and hearing protectors as they affect industrial accidents. The authors stated additional concerns and, in some places, made more conservative recommendations.

Following earlier investigations of the effect of ear protection status,[248,249] Tufts and Frank found that talkers wearing earplugs versus no protection produced lower overall speech levels, lower speech-to-noise ratios, lower Speech Intelligibility Index values, and less high-frequency speech energy.[250] Some recent investigations of the effects of HPDs on localization have concentrated on the effects of double protection (muffs over plugs), indicating severe disruptions relative to the unoccluded condition.[251–253] An investigation by Simpson et al[253] revealed significantly greater adverse effects on localization from the combination of plugs and muffs than from either HPD alone. The effect was almost as severe as the no-cue condition, leading the investigators to seriously question the safety of double protection in certain working conditions. These findings raise serious safety implications for policies and regulations that require double protection in high noise levels, such as the MSHA noise regulation.

Several kinds of special HPDs have been developed to enhance speech communication and warning signal detection during noise exposure and to permit them during quiet intervals. These include both passive and active attenuators. Speech intelligibility testing with both types indicates performance advantages under some conditions but not others. Electronic devices have been improved over recent years, but problems with insufficient attenuation as well as adequate communication still occur.[254]

A series of studies by Casali et al[255] tested the ability of hearing enhancement protection systems to improve the ability of soldiers to detect important signals such as communication, enemy presence, and distance estimation. They found that electronic sound transmission devices offered some improvement over passive systems but that ergonomic challenges associated with their use remain to be solved. Azman and Yantek[256] investigated the performance of sound restoration hearing protectors by using the Speech Intelligibility Index in different background noises and with various device settings (passive, half on, one-quarter on, three-quarters on, maximum). One-third-octave band data were acquired from nine of these devices on a G.R.A.S. acoustic test fixture (G.R.A.S. Hearing-Protector Test Fixture Type 45CA; G.R.A.S., Copenhagen, Denmark). The Speech Intelligibility Index was applied to these data to determine the devices and settings with the best estimated performance so that these could be used for human subject–based speech intelligibility testing. Overall, it was found that performance varied little between most of the devices, with few showing exceptionally good or poor estimated speech intelligibility. The most significant differences in estimated performance using the devices were between the different background noise sources used, regardless of the device or device setting.

RESEARCH NEEDS

- Develop practical methods to determine the effects of HPDs and hearing loss on recognition of necessary signals in noisy environments.

- Systematically investigate the role of noise, hearing loss, and HPDs in accidents resulting in injuries and fatalities.
- Estimate the costs of noise-related accidents to industry and to the U.S. economy.
- Continue investigation of the adverse effects of various kinds of HPDs on speech communication, warning signal identification, and localization.
- Develop alternatives to double hearing protection in conditions that necessitate the recognition of audible warning signals.
- Develop practical, cost-effective technologies to improve audibility of speech and other important signals in noisy environments.

Hearing-Critical Jobs

Learning Outcomes: As a result of this activity, the participant will be able to describe the characteristics of a hearing-critical job and criteria used to qualify a worker for a hearing-critical job.

Jobs for which some level of hearing ability is necessary to complete the associated tasks and in which failure to complete the tasks could negatively impact safety and/or productivity are known as *hearing-critical jobs*.[257] Such jobs often involve noisy environments and require hearing functions such as signal detection, sound localization, or verbal communication.[258] Examples of hearing-critical jobs include firefighting, police work, air traffic control, and construction. Identification of hearing-critical jobs and evaluation of workers' fitness to accomplish them are essential to both safety and production. The results of missed supervisory directions, lost acoustic signals from machinery, and unheard warning signals can be catastrophic. At the same time, however, discrimination against workers who have hearing impairment must be avoided. The Americans with Disabilities Act of 1990 specifically prohibits discrimination against qualified workers who have a disability and requires that reasonable accommodations be made to allow such workers to function safely in their jobs.[259] Since its passage, Congress has amended the Act to expand the definition of disability and to reject several judicial decisions that had narrowed the definition.[260]

Historically, there has been little uniformity in criteria for identifying which jobs are truly hearing-critical or defining the specific auditory abilities necessary for given tasks. MacLean[261,262] summarized the hearing standards utilized by various governmental and military agencies and noted little consistency across the specified auditory requirements. Most criteria are based on either pure-tone audiometric thresholds or uncalibrated speech tests (e.g., the forced-whisper test). Pure-tone sensitivity may not be well correlated with functional performance at suprathreshold levels, as indicated by the broad range of word discrimination scores possible among persons with the same pure-tone audiogram.[257,258] The forced-whisper test is subject to significant variability in the SPL of word presentations.[263] Valid methods are needed for defining the auditory requirements of specific jobs.

Several approaches have been proposed. Punch and colleagues[264] developed a three-tiered approach for Michigan law enforcement officers, based on pure-tone thresholds and speech discrimination in quiet and noise. The approach was based on a job task analysis; it is efficient in that officers with normal pure-tone thresholds do not need to complete additional testing. However, no follow-up study of the effectiveness of these criteria has been reported. Begines[265] reported an evaluation procedure based on five damage-risk criteria: physical impairment (audiometric and medical examination), job communication requirements (a four-point scale based on necessity of communication, proximity to source, and availability of visual cues or communication aids), functional impairment (employee-reported hearing ability along parameters such as localization and ability to hear in noise), shop safety requirements (dangers inherent to the job task), and history of on-the-job injuries. The procedure utilizes readily available data and integrates much more information than merely hearing thresholds. Again, however, there has been no published follow-up of the effectiveness of this approach.

Canadian researchers have adapted the Hearing In Noise Test (HINT)[266] to predict worker performance in hearing-critical jobs.[257,258] Extensive normative data and complete psychometric functions are available for the HINT, which can be conducted under headphones or in the sound field, and the test takes about 2 minutes to complete. Sample noises were recorded directly from work sites and incorporated into the HINT system. Scores were obtained for normal-hearing and hearing-impaired subjects exposed to these noises, and models were developed to predict real-world intelligibility. Minimum HINT scores for individual job tasks were then established. The approach resulted in substantially better predictions of worker performance than with pure-tone audiometric thresholds. However, incorporating noise recordings from individual work sites and establishing the predictive model may not be feasible for many work sites.

The Canadian HINT studies[257,258] identified several other issues that warrant further research. First, even persons with normal hearing exhibited difficulty in some listening situations. Tasks in which no one can effectively perform the necessary auditory functions must be identified, and adaptive strategies must be developed to maintain safety in these situations. Second, workers who can initially perform the necessary auditory tasks may develop hearing difficulty later in their careers. Periodic evaluation of employees in hearing-critical jobs is necessary, and research is needed to establish the most efficient timing for such evaluations. Third, factors other than hearing ability may influence a worker's capacity to function in hearing-critical environments. For example, more-experienced workers may function better than their test results would predict, and tasks that require a greater cognitive load may result in a poorer performance than predicted. Methods of accounting for these factors in determining an individual's fitness for work would improve the accuracy of the evaluation.

RESEARCH NEEDS

- Identify criteria for classifying job tasks as hearing-critical.
- Develop standardized procedures to predict a worker's auditory performance in hearing-critical situations; it should be possible to apply these procedures with uniformity across occupations and industries.
- Validate previously proposed methods through field studies comparing actual worker safety and worker performance to predictions.
- Determine ways to incorporate nonauditory influences, such as individual experience and the cognitive load of a task, in evaluations of a worker's ability to function in hearing-critical situations.

Nonoccupational Noise Exposure

Learning Outcomes: As a result of this activity, the participant will be able to identify the relationship of recreational noise exposure to hearing loss.

Over recent years the scientific and hearing conservation communities have paid considerable attention to the threat of hearing loss from nonoccupational exposures, such as loud music, noisy leisure time activities, shooting, and even the noise from traveling in a car or bus. Typical of this concern is a comprehensive review by Axelsson[267] in which the author states that although improvements are occurring in occupational noise exposure conditions, recreational noise conditions are probably deteriorating.

The effects of nonoccupational noise exposure are particularly evident among youths. According to some studies, hearing threshold levels in young people increasingly show the characteristic "noise notch" even for those who do not report noise exposure incidents or activities.[268]

The traditional culprit, especially according to parents, has been loud music. However, researchers such as Axelsson point out that typical exposure times and the number of exposures per year are limited, and impulsive sources such as weapons, firecrackers, cap guns, and other noisy toys can be more dangerous.[267] This concern is reflected in a study of acoustic trauma due to firecrackers, in which the incidence of acoustic trauma due to firecrackers was much higher among 19-year-old males than among females or older age groups.[269]

Most recent efforts to investigate the effects of loud music have examined special groups, which include not only participants, such as those in aerobics classes,[270] but also employees, such as students working in entertainment venues,[271] music teachers,[272] and rock musicians.[273] Not surprisingly, the investigators found that potentially hazardous noise levels were common, as were reports of tinnitus. They also found a TTS (when measured) in many participants and a high incidence of permanent threshold shift.[271] One study showed a significant difference in the hearing threshold levels of musicians who regularly used HPDs and those who never used them,[273] although the prevalence of HPD use among musicians is not well known.

Some studies have measured the actual off-work noise exposures of workers. In recent studies of construction workers, Neitzel et al[274,275] found that average exposures away from work tended to be below 80 dBA. They found that 79% of the construction workers studied had average (calculated with the 3-dB exchange rate) off-work exposures below 70 dBA.[274] In a longitudinal study of construction apprentices, they found an average nonoccupational exposure of 78 dBA.[275] These results are consistent with the mean 24-hour average exposure level of 78 dBA measured earlier by Berger and Kieper[276] for 20 subjects, most of whom were nonoccupationally exposed. However, Neitzel and colleagues did not include noise levels from firearms because of a lack of consensus on the method by which impulse noise should be included in the resulting measurement. They concluded that for shooters, who comprised 22% of the apprentices, the average nonoccupational exposure level would be higher.

Although there seems to be a common perception that nonoccupational exposures are increasing, results of population studies show little change in the hearing of young adults over recent decades. In their report on a Swedish study of 611 boys, the authors concluded that the hearing of 18-year-old military conscripts was no poorer in 1998 than that measured 29 years earlier.[277] In the United States, Rabinowitz and colleagues examined baseline audiograms of 2526 beginning employees between 1985 and 2004 and found that the occurrence of audiometric "notches" remained consistent over the 20-year period.[278]

RESEARCH NEEDS

- Create consensus on a measurement method and gather information on the contribution of impulse noise to the total burden of nonoccupational noise exposure.

- Develop incentives for manufacturers to reduce the noise levels of recreational equipment.
- Develop incentives for the general population to encourage the use of HPDs during engagement in noisy recreational activities.

Tinnitus

Learning Outcomes: As a result of this activity, the participant will be able to describe the characteristics and mechanisms currently thought to be associated with tinnitus, as well as the principles related to the management of tinnitus.

In 2005, the National Academies Institute of Medicine published a report entitled *Noise and Military Service: Implications for Hearing Loss and Tinnitus*, the result of lengthy deliberations of the Committee on Noise-Induced Hearing Loss and Tinnitus Associated with Military Service from World War II to the present.[279] Chapter 4, "Tinnitus," was very helpful in the preparation of this section, and many of the references cited in this section are also cited in the Institute of Medicine report.

Tinnitus is a subjective sensation of sound often referred to as *ringing in the ears*. It is common in the U.S. population, and its effects can range from a minor annoyance to a mental health problem prompting suicidal tendencies, although such extreme cases are rare. Its onset can be gradual or sudden, and it is usually accompanied by hearing loss. It is not unusual for tinnitus sufferers to say that their tinnitus bothers them more than their hearing loss. One measure of the level of serious tinnitus in the population is the percentage of people with tinnitus who seek medical care. This percentage has been estimated as 14 to 25%.[280,281] According to recent surveys, the prevalence of tinnitus (of any severity) in the U.S. adult population is between 4 and 8%,[282,283] although it depends on the definition of tinnitus used in the questionnaires. Tinnitus is more common in older populations and in people who have been exposed to noise. It is a significant problem for veterans, and service-connected tinnitus involves expenditures of hundreds of millions of dollars by the Veterans Administration every year (see discussion in "Economic Impact of Occupational Hearing Loss" section, (pgs. 176–181)).

The etiology of tinnitus is thought to be similar to that of hearing loss. According to Coles,[284] the same factors that caused the hearing loss probably also caused the tinnitus. If NIHL is present, there needs to be "strong contrary evidence for tinnitus to be diagnosed as due to something else."[284(p.13)] The neuroscience community recently has conducted substantial research on the mechanisms of tinnitus. The Institute of Medicine report suggests that the effects of noise exposure and hearing loss "disrupt the delicate balance between excitation and inhibition in the central auditory pathways."[279(p.118)] The report cites a study implicating the dorsal cochlear nucleus as a possible generator site for tinnitus,[285] although questions about mechanisms need further resolution.

There is considerable ongoing research in the medical and clinical audiology communities on assessment and treatment of tinnitus. Professionals in tinnitus research and treatment prefer to use the word *management* rather than *cure*, because there is no known cure.

The assessment of tinnitus involves self-reporting by patients and the use of psychoacoustical techniques of matching pitch and loudness under clinical conditions. Several self-report questionnaires are available to assess the impact of tinnitus (e.g., Kuk et al,[286] Wilson et al,[287] and Newman et al[288]), asking subjects to rate statements about the effect of tinnitus on their lives.

Treatment involves mainly counseling, sound therapies, and medication (see Dobie[289]). Some recent developments in tinnitus treatment have resulted from studying the role of the brain and central nervous system. "Tinnitus Retraining Therapy," for example, is based on neurophysiological models aimed at reducing reactions in the limbic and autonomic nervous systems.[290] Scientists at the University of Buffalo are working to identify the neural signatures of tinnitus, using techniques such as functional magnetic resonance imaging and molecular-level positron emission tomography imaging with the goal of developing potential therapeutic drugs to suppress the adverse effects.[291] Drugs that would mitigate the adverse effects of tinnitus would be very beneficial to severe tinnitus sufferers.

The preponderance of evidence from cross-sectional studies points toward a higher prevalence of tinnitus in noise-exposed versus non-noise-exposed populations, although reports of its prevalence vary widely. As examples, prevalence rates were found to be 7% among workers in British Columbia,[292] 18% among certain Australian workers,[293] 28% among U.S. steel workers,[294] 76% among Polish drop-forge operators,[295] and 88% among Egyptian forge workers.[296] Another Australian study showed the relative risk of having tinnitus was significantly related to the severity of noise exposure.[297] Many factors may affect these differences in prevalence, including noise level, duration of noise, type of noise, use of HPDs, age of the subjects, and individual variability. The same kinds of factors influence the amount and type of NIHL. It does appear, however, that impact noise, such as forging noise, may be a more significant contributor to tinnitus than more continuous types of noise.

There is also an indication that impulse noise increases the risk of tinnitus, although again, the study results appear to be mixed: some studies show the risk is greater than with continuous noise,[283] whereas others show no significant differences.[298]

The prevalence of tinnitus associated with acoustic trauma has also been studied. Some 67% of the survivors of the Oklahoma City bombing reported having tinnitus soon after the blast, and 59% had tinnitus after 5 months.[299] The prevalence of tinnitus among military personnel exposed to a blast also appears to be high, ranging from 62 to 84%.[279] There seems to be little information, however, on the course of recovery from tinnitus caused by traumatic exposures.

Prospective tinnitus studies of populations exposed to different types and levels of noise would be useful, as they would for hearing loss effects. Such investigations become extremely difficult to control in current times, however, because of the widespread—even obligatory—use of HPDs, which attenuate the noise level and change the spectrum to an unknown extent. These kinds of studies could be conducted by means of on-site measurements with microphones placed beneath the HPDs.

There appears to be a positive relationship between tinnitus and existing hearing loss. Not surprisingly, the prevalence of tinnitus is greater among people with hearing loss than among those with normal hearing. One cross-sectional investigation showed no association between tinnitus and noise exposure level or duration among subjects with normal hearing, but it revealed a positive association among subjects with hearing loss.[300] In addition, a large longitudinal study of older adults showed that the preexistence of hearing loss increased the risk of developing tinnitus over a 5-year period.[298] The possibility of hearing loss predisposing individuals to tinnitus needs to be explored further, especially with non-noise-exposed working-age populations so as to avoid contamination both by noise and by the use of HPDs.

There seems to be little information available on the prevalence of tinnitus among workers exposed to combinations of noise and ototoxic agents, such as chemicals, carbon monoxide, vibration, and other workplace hazards. However, the contribution of other health risks has been studied. For example, some large studies have found significant associations with head injury, neck injury, cardiovascular disease, and poor self-reported health status.[279] A recent trial of a low-cholesterol diet and antihyperlipidemic therapy for subjects with high-frequency hearing loss and tinnitus due to noise exposure showed promise for alleviating tinnitus, also indicating that blood chemistry could be a causal factor.[301]

Although tinnitus is often mentioned in the conduct of hearing conservation programs, it is usually limited to a question in a brief medical history calling only for a yes-or-no response. Little is done to obtain information about the onset, temporal characteristics, and degree to which it affects the worker's life. In addition, hearing conservationists seldom mention tinnitus in their educational programs, even though workers frequently report that their tinnitus bothers them more than their hearing loss. Some professionals maintain that tinnitus is easier for young workers to relate to than hearing loss and would be a more effective educational topic.[302]

An important yet underappreciated factor in hearing loss is the usefulness of tinnitus as an early warning signal for NIHL. A retrospective study of 91 steel foundry workers showed that tinnitus was reported an average of 5.8 years prior to the maximum threshold shift.[303] Further investigation with larger industrial populations would be useful.

Although tinnitus is often a factor in workers' compensation claims, again it is most often mentioned only in a question relating to its presence or absence. Considerable progress has been made toward objectifying the psychoacoustic characteristics of tinnitus[304] and designing procedures for a basic tinnitus assessment. The details of such an assessment, including an intake interview, audiological evaluation, and psychoacoustic assessment, have been described by Henry and coauthors.[305] There is consensus, however, that the relationship between tinnitus sensation and its impact on an individual is weak.[306] Several useful questionnaires are available to assess the distress, disability, and handicap encountered by those with tinnitus, and several of these have demonstrated internal consistency and good test-retest reliability (see review by Newman and Sandridge[306]). Not much information is available about questionnaire standardization, with the exception of the Tinnitus Handicap Questionnaire,[286] in which the authors provide a means for comparing individual scores with their own published normative data for tinnitus patients. Recently, a substantial collective effort has been completed by 21 investigators (representing 10 clinical centers in the United States and one in New Zealand) to provide a tinnitus questionnaire that integrates the experience gained from previous questionnaires and that may well become a standardized means of measuring the severity and negative impacts of tinnitus. The new questionnaire has been validated both as an assessment instrument for evaluating prospective tinnitus patients or research subjects and as a responsive outcome measure for use in clinical trials.[307]

Questions about the characteristics, mechanisms, assessment, and treatment of tinnitus are being studied extensively at research centers throughout the United States and in other countries. Despite the successes in tinnitus research, more emphasis is needed on the practical application of information about tinnitus in the workplace. What is most needed is a transfer of the resulting information to the purveyors of hearing conservation programs in the workplace to enable hearing conservationists to deal more effectively with the assessment and prevention of tinnitus, as well as accommodations for this condition. Seminars, workshops, and other means of bringing research findings to those who practice hearing loss prevention in the workplace would help accomplish this goal.

RESEARCH NEEDS

- Continue research on the use of tinnitus as a predictor of NIHL, including study of the occurrence of tinnitus without hearing loss in noise-exposed populations, as well as long-term follow-up.
- Investigate the extent to which an existing hearing loss predisposes to development of tinnitus.
- Continue research on the onset and progression of tinnitus in noise-exposed workers, especially the possibility of delayed onset.
- Evaluate the effects on tinnitus of ototoxic agents in the workplace, alone or in combination with noise.
- Determine whether impulse and impact noise affect tinnitus more severely than other types of noise.
- Develop further tools to assess, evaluate, and define noise-induced tinnitus for hearing conservation purposes.
- Investigate the effect of otoprotectants on tinnitus.

Extra-Auditory Effects of Noise Exposure

Learning Outcomes: As a result of this activity, the participant will be able to describe the nature of and evidence associated with extra-auditory effects.

There are other adverse effects of noise, in addition to hearing loss, tinnitus, and communication interference. These effects are mediated through the auditory system, although they do not impact audition and are thus extra-auditory. The extra-auditory physiological effects include adverse changes in blood pressure and chemistry, and there is evidence of other effects, which manifest as performance decrements, accidents, and absenteeism. Many investigators link noise exposure with stress and therefore with the so-called stress diseases.

Noise has been implicated in a wide variety of health problems, ranging from hypertension to psychosis. Some of these findings are based on carefully controlled laboratory or field research, but many others are the products of studies that have been severely criticized by the research community.[308] Obtaining valid data can be difficult because of the great number of intervening variables that must be controlled, such as age, selection bias, preexisting health conditions, smoking status, alcohol abuse, socioeconomic status, exposure to other agents, and environmental and social stressors. Interpretation of the findings can also pose difficulties related to the differences between humans and animal models and the implications of acute effects for chronic conditions.

Noise is considered a nonspecific biological stressor, and thus it can influence the entire physiological system. Noise acts in the same way as other stressors, causing the body to go through a series of biological changes, preparing either to fight or to run away—the classic fight-or-flight response (or nowadays, the "fight, flight, or freeze" response). Although these changes may be benign in the short term, there is evidence that they persist with chronic exposure to high noise levels, even though an individual may be unaware of them. Most of the effects appear to be transitory, but with continued exposure some adverse effects have been shown to be chronic in laboratory animals. The evidence is probably strongest for cardiovascular effects, such as increased blood pressure and changes in blood chemistry.

Current thinking holds that the extra-auditory effects of noise are most likely mediated through aversion to noise, making it difficult to obtain dose–response relationships (e.g., see Melamed et al[235]). Rovekamp[309] found that subjects who described themselves as sensitive to noise showed significantly greater noise-induced increases in peripheral vasoconstriction than their "normal" counterparts. Ising and colleagues[310] stated that the difference between subjective and objective noise rating is important, and they concluded that noise acts indirectly by disturbing activities and leading to psychophysiological stress, which in turn produces adverse cardiovascular effects.

A significant set of laboratory studies on primates showed chronically elevated blood pressure levels resulting from exposure to noise around 85 to 90 dBA, which did not return to baseline levels after exposure cessation.[311–313] Several studies of industrial workers show similar effects, but results have been equivocal. Rehm,[314] who reported on six laboratory investigations with human subjects who showed increases in blood pressure, questioned whether these effects would be permanent. Rehm also reviewed 14 field studies, mostly of occupational noise exposure, and reported that the majority showed significant increases in systolic blood pressure, diastolic blood pressure, or both.[314] In another review, 12 cross-sectional studies were analyzed; half of them showed a positive relation between noise exposure and blood pressure, and the others showed no significant effects.[315] It should be noted that these kinds of investigations are considered to have several methodological weaknesses, including inadequate description of noise and blood pressure measurements, absent or inadequate control of intervening variables, use of hearing loss as a determinant of exposure magnitude, variable use of hearing protectors, and questionable interpretation of the results.[315] A more recent review, by Stansfeld and Matheson,[316] included seven additional studies of noise exposure and blood pressure; most of the studies had positive findings, although some results were not confirmed in multivariate analysis.

Several studies of noise-induced changes in blood chemistry showed increased levels of the catecholamines epinephrine and norepinephrine due to noise exposure (see studies cited in Rehm,[314] Stansfeld and Matheson,[316] and Ising et al[317]). A series of experiments by German investigators revealed a connection between noise exposure and magnesium metabolism in humans and animals.[310,317] The investigators discovered an interaction between endocrine reactions, such as increased catecholamines and a shift in the balance of intracellular calcium and magnesium, which leads to pathological alterations in the myocardium and the vascular walls. In animal research, they found that chronic stress caused a depletion of magnesium and an increase in calcium, and they concluded that magnesium and noise are stressors that act synergistically. These findings led to the hypothesis that chronic noise-induced stress increases the risk of myocardial infarction (MI). They tested this hypothesis in a case–control study of 395 patients with MI and 2148 controls. After controlling for several variables, they found that the relative risk of MI increased significantly with the subjectively scaled level of noise in the workplace. Second to smoking, workplace noise was associated with the highest risk of MI.[310]

In a recent review of the effects of noise on hearing, Babisch[318] summarized results of several European analyses. Most of these analyses focused on traffic noise studies, but several included studies of occupational noise. Of particular interest were four Dutch reviews that found limited evidence of a relationship between noise and biochemical effects and sufficient evidence of a relationship between noise and hypertension as well as noise and ischemic heart disease. A British group determined that there was inconclusive evidence of a causal link between noise and hypertension but sufficient evidence of a causal association between noise exposure and ischemic heart disease. *Limited evidence* was defined as a positive association with a credible causal interpretation, but for which chance or bias cannot be ruled out. *Sufficient evidence* was defined as a positive relationship for which chance and bias can be ruled out with reasonable confidence.[318] The author refers to a meta-analysis by van Kempen et al[319] in which the investigators concluded that the epidemiological evidence linking noise exposure with blood pressure and ischemic heart disease is still limited. Although both the Dutch and British groups presented positive conclusions, at least for ischemic heart disease, further analyses focusing exclusively on occupational exposure would be beneficial.

An extensive cross-sectional, longitudinal study of industrial workers was undertaken by Melamed and colleagues. In three phases over a period of more than a decade, the investigators examined the cardiovascular and psychological effects of noise exposure on a large population of Israeli workers. They found significant effects on the incidence of cardiovascular morbidity and mortality and on total mortality, even after controlling for possible confounding variables.[320] They also found that the effects of noise were dependent upon certain psychological factors, resulting in higher levels of cholesterol and high-density lipoproteins in subjects annoyed by noise,[321] and they noted increases in blood pressure in subjects performing complex jobs in high noise levels but not in low noise levels.[322] The implications of these studies are important and deserve further exploration. To the extent that they apply universally, the effects should be considered widespread and serious.

Some investigations have attempted to find a correlation between NIHL and extra-auditory effects (see also "Factors Influencing Susceptibility," pgs. 168–170). A study to assess relationships among occupational noise exposure, NIHL, and high blood pressure among retired workers showed that severe NIHL was a predictor of hypertension among the older retirees but not among the younger ones.[323] Another study showed that subjects with low levels of physiological arousal—and, consequently, lower serum cortisol levels—actually evidenced more TTSs than persons with higher levels of physiological arousal.[324] Thus, it does not appear that the degree of NIHL is an indicator of noise stress, either acute or chronic.

The effects of noise on job performance have been studied both in the laboratory and in the occupational setting. The results have shown that noise usually has negligible effects when the task is repetitive and monotonous, and in some cases it can actually increase job performance when the noise is low or moderate in level. High levels of noise can degrade job performance, especially when the task is complex or involves doing more than one activity at a time. Intermittent noise tends to be more disruptive than continuous noise, particularly when the periods of noise are unpredictable and uncontrollable. Research indicates that people are more likely to exhibit antisocial behavior in noisy environments than in quiet ones and are less likely to engage in helpful behavior. (For a more detailed review of the performance effects, see Suter.[234])

Because the extra-auditory effects of noise are mediated by the auditory system, properly fitted HPDs should reduce the likelihood of these effects in the same way they do for hearing loss. A classic study of the effects of a hearing protection program on 400 boiler plant workers was conducted by Cohen,[215] who compared certain parameters before and after the institution of the program. The results showed fewer injuries, medical problems, and absences after the program was instituted. Another investigation, by Melamed et al,[235] showed increases in accidents and illness-related absences among workers exposed to high noise levels. The investigators also found that these effects were significantly more common among noise-annoyed workers. Confirmation of these results and the implication for workplaces in the United States would be useful.

RESEARCH NEEDS

- Perform a meta-analysis of data examining the relationship of occupational noise exposure to hypertension and ischemic heart disease.
- Initiate a team effort to review evidence and build consensus toward development of dose–response relationships.
- Further elucidate the relationship between noise characteristics (level, frequency, and temporal pattern) and adverse endocrine effects.
- Further investigate the role of aversion to noise in the occurrence of adverse cardiovascular and other physiological effects.
- Conduct field studies to examine the ameliorative effects of interventions such as noise-source control and HPDs on adverse health occurrences.

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