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National Research Agenda for the Prevention of Occupational Hearing Loss

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INTRODUCTION

National Research Agenda for the Prevention of Occupational Hearing Loss

Occupational hearing loss is the most common work-related injury in the United States. Although the estimates vary, it is thought that ~22 million U.S. workers are exposed to hazardous noise levels at work, and an additional 9 million are exposed to ototoxic chemicals, which also can lead to hearing impairment. A significant but unknown number of workers have suffered a work-related hearing loss. The problem crosses many occupational sectors, including manufacturing, construction, transportation, agriculture, and the military. Hearing loss resulting from noise or chemical exposures is permanent. It is also preventable. In addition to hearing loss, many workers suffer from noise-induced tinnitus (ringing in the ears) and face the possibility of noise-related accidents and other adverse health effects.

Most occupational hearing losses develop gradually as the result of metabolic processes due to chronic exposure, but hearing loss can also develop instantaneously from acoustic trauma, in which a single, hazardous noise mechanically damages the delicate structures of the ear. When the Occupational Safety and Health Administration (OSHA) issued its hearing conservation amendment in 1981, the agency estimated that, at that time, more than 1 million workers in the manufacturing industries had developed a material impairment of hearing. Noise is the most common hazard that leads to occupational hearing loss; but exposure to solvents, metals, asphyxi-

ates, pesticides, heat, and other physical or chemical agents also may affect workers' hearing. Hearing damage is cumulative and often does not become apparent until substantial, irreversible injury has occurred.

The type of hearing loss caused by noise or chemical exposure is categorized as sensorineural. Vulnerable sensory cells and nerve fibers in the cochlea are slowly damaged and destroyed. Neural signals transmitted to the brain for interpretation as sound are diminished or lost. No treatment exists to reverse or repair the effects of noise or chemical exposures on the auditory system.

Hearing impairment has significant consequences for workers, both on and off the job. A diminished ability to communicate with coworkers or monitor sounds in the work environment (e.g., warning signals, equipment sounds, backup alarms) can reduce productivity and place workers at increased risk for accidents. The increased effort required for communication can cause stress and fatigue. Quality of life may be diminished as the hearing-impaired individual faces difficulty communicating with family and friends and misses such pleasures as enjoying music, hearing children's voices, and listening to sounds in nature. It is not unusual for hearing impairment to lead to social isolation and depression. In addition to the difficulties posed by loss of hearing, other adverse effects of exposure (such as tinnitus) may further increase a worker's debilitation.

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National Research Agenda for the Prevention of Occupational Hearing Loss; Guest Editor, Mark R. Stephenson, Ph.D.

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In 1996, the National Institute for Occupational Safety and Health (NIOSH) established the National Occupational Research Agenda (NORA) as a framework to guide research and focus efforts to prevent work-related illness and injury. The NORA program is a partnership that seeks to involve all stakeholders in occupational safety and health, including businesses, worker organizations, professional societies, universities, and government agencies. Over 500 organizations and individuals outside NIOSH contributed to the development of the original research agenda. The NORA goal is to identify the most critical workplace hazards and work together to address them.

The original NORA program identified 21 research priorities based on the number of workers at risk, the severity of the hazard or outcome, and the probability that new research would have an impact on reducing the particular illness or injury. Occupational hearing loss was included among the original priority areas. In 2006, NORA was reorganized by industrial sectors. Because noise exposure affects so many different industries, hearing loss was retained as a NIOSH cross-sector program that addresses NORA sector priorities.

The NORA Hearing Loss 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. In 2009, the document was updated and expanded to reflect progress in noise-related research over recent years.

This white paper is organized into two primary sections. The first outlines areas in which the adverse consequences of occupational

noise require further definition. Research is still needed to estimate the prevalence of noise and other ototoxic exposures in the workplace, to measure progress in reducing or eliminating those exposures, to define the risk posed by various agents, and to understand the mechanisms of damage. In addition, there are unresolved questions regarding the auditory and extra-auditory effects of noise and other occupational exposures on workers, as well as the personal and professional impact of these effects on workers. The second section outlines research needed to address the problem through prevention programs. These programs have many aspects, including noise measurement and control, hearing protection, audiometric monitoring, training and motivation, record keeping, and program evaluation. Each of these areas could benefit from the development of innovative techniques to improve their effectiveness or to extend their application to underserved populations.

In developing the research agenda, the NORA Hearing Loss Team endeavored to highlight topics appropriate for both basic and applied research. Basic research involves development of better methods of understanding and preventing hearing loss in the future; applied research involves current prevention of hearing loss and other adverse effects. Both types of research are essential to reducing the burden of occupational hearing loss. However, in keeping with the NIOSH vision of "safety and health at work for all people through research and prevention," more emphasis has been placed on applied research needs that could have a more immediate impact on reducing the burden of occupational hearing loss.

Mark R. Stephenson, Ph.D.¹
Guest Editor

PREFACE

Executive Summary

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 one of the original 21 priority research areas, 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. To best accomplish its goal of identifying needed research to prevent occupational hearing loss, the document is divided into two major sections: (1) defining the problem and (2) addressing the problem.

The first major section, "Defining the Problem," includes 14 subsections. 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.

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. And 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.

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The second major section, "Addressing the Problem," has 11 subsections that are focused on more applied elements of occupational hearing loss prevention programs. Although there are many unanswered questions regarding the nature and scope of occupational hearing loss, it is not necessary to resolve all of them before acting to reduce the problem. In fact, from a certain standpoint, addressing the problem is especially important because it can have an immediate impact on reducing the incidence of occupational hearing loss. In reality, of course, these two arms of research must be accomplished simultaneously, the former informing the latter and the latter providing feedback to the former.

Traditionally, the occupational noise problem has been addressed through the establishment of effective hearing loss prevention programs. These programs typically involve seven components: noise measurement (to identify persons at risk), noise control (to remove the hazard insofar as possible), hearing protection (to prevent hearing loss when noise levels cannot be sufficiently reduced), audiometric monitoring (to ensure that protective measures are adequate), training and motivation (to encourage workers to engage in protective behaviors), record keeping (to permit evaluation of successes and failures), and program evaluation (to identify and correct program weaknesses). This section of the document focuses on each of these components in turn, describing what has worked, what might work even better, and what questions need to be answered to develop more effective approaches to hearing loss prevention.

In addition, this section identifies unique populations with special hearing loss prevention needs and discusses research that would enable these groups to be better protected against occupational hearing loss. This section also addresses treatment and rehabilitation issues for the many workers who have already sustained a work-related hearing impairment. Finally, the need to take hearing loss prevention beyond the occupational arena and into the overall public health arena is discussed.

In the past, NIOSH research has focused primarily on noise as the problematic exposure and hearing loss as the preventable outcome. However, exposure to ototoxic chemicals and outcomes such as tinnitus and various other adverse effects of noise have gained prominence in recent years. Although these additional exposures and effects are discussed in this document and related research has been recommended, most of the measures integral to programs for prevention of hearing loss—in particular, engineering noise control—could be expected to reduce the likelihood of these other adverse effects as well. In some cases, however, care must be taken that reducing one exposure does not increase another.

Because each of the 25 subsections addresses a specific issue, such as mechanisms of noise-induced hearing loss, extra-auditory effects of noise exposure, noise control, and audiometric monitoring, each subsection can be thought of as a stand-alone discussion of the topic area. As such, each subsection has its own list of research needs. It should be noted that the NORA team elected not to list research needs in any specific order. This was in recognition of the fact that between work sectors, research needs would vary; the needs most highly prioritized in the mining sector, for instance, might be different than in the services or manufacturing sectors. Rather than providing a prioritized list of research topics, with the current document the team sought to provide a comprehensive assessment of the current state of hearing loss prevention technology and to provide broad direction for future research. However, NIOSH has adopted a strategic plan that does include prioritized research goals for preventing occupational hearing loss. More information about these prioritized research goals can be obtained on the NIOSH Web site, at www.cdc.gov/niosh/programs/hlp/goals.html.

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Guest Editor

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

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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.

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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 occupations¹⁻³ 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 measure-

ments 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.

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 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 Administration² and the National Institute for Occupational Safety and Health.³

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 from 1984 to 1989, 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 McCullagh¹³ 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 al¹⁹ 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 com-

mon 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

Average Exposure Level, dBA	Definition of Material Impairment									
	0.5-1-2k Hz definition					1-2-3k Hz definition			1-2-3-4k Hz definition	
	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 world³² 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 coauthors³⁵ 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 1999³⁷ 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 un-screened 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 1999³⁷ 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 coworkers⁵⁰ 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 Rosenhall⁵⁶ 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 al⁵⁹ found that, consistent with previous research findings (e.g., Royster et al⁴⁰), 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 al⁵⁹ 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 non-smokers,^{60,61} although a study by Gates et al⁶² did not. Mizoue et al⁶³ 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 al⁶⁸ 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 al⁷² 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 al⁶⁸ 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 Ward⁷⁴ proposed criteria for a trading relation between intensity and the number of impulses. Atherley and Martin⁷⁵ were among the first to extend the equal-energy rule (L_{eq}) to noise environments with impulse and impact noise. Later, Passchier-Vermeer⁷⁶ 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. Spoenclin⁷⁷ suggested this level to be 130 dB, and Hamernik and Hsueh⁶⁹ estimated it to be 140 dB, noting that most industrial impacts would be below that level. Price⁷⁸ 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).
- AHAHAH, 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 al⁸⁷ 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 model⁸⁸ 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 Johnson⁹¹ 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 al⁹² analyzed the criteria of the four NATO countries (the models outlined

above, with the exception of AHA AH), 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 Ho⁹³ analyzed the AHA AH model against the same TTS human data from the BOP. As a result, the authors were critical of the AHA AH 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 Ho⁹⁴ 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, AHA AH 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 al⁸³ 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 al⁹⁵ 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 Hamernik⁹⁸ cited the finding of Ceypek et al⁹⁹ that a combination of impact and continuous noise produced a greater effect than equal energy would predict. They cited the findings of Luz and Hodge¹⁰⁰ 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 studies¹⁰⁴⁻¹⁰⁶ 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 al¹⁰³ 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 Qiu¹⁰¹ 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 al¹⁰⁷ 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 al¹⁰⁸ 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 al¹⁰⁹ 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 β 50 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 al¹¹¹ 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 Medicine¹¹⁶ 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. Hager¹²⁶ 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 Calvert¹³² 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 surveillance¹¹⁷ 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 Schacht¹⁴⁰) 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 dam-

age. 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 al¹⁵¹ 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 colleagues¹⁵² 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 Liberman⁵⁸ 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 colleagues¹⁵⁴ 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 Liberman⁵⁷ found similar results. However, Boettcher¹⁵⁵ 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 Humes¹⁵⁷ and Henderson et al¹⁴⁹ (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 al¹⁶¹ 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 Williams¹⁶² 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 Williams¹⁶² 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 colleagues¹⁶⁷ 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 colleagues¹⁶⁸ 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 al¹⁶⁹ 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 al¹⁷⁰ 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 colleagues¹⁷¹ 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 colleagues¹⁷³ reported that SOD2 polymorphisms were associated with increased susceptibility to NIHL among 94 male workers in an aircraft factory. Carlsson et al¹⁷¹ found no evidence of increased susceptibility to NIHL in CAT1, CAT9, SOD5, and SOD6 with polymerase chain reaction analyses. More recently, Konings et al¹⁷⁴ 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 al¹⁷⁷ 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 al¹⁷⁷ 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 al¹⁷⁸ 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 al¹⁸¹ 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} Fechter¹⁸³ 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. Fechter¹⁸³ 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 Fechter¹⁸³

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 Morata¹⁸² 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 studies¹⁹¹:

- 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 2001³⁸), 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

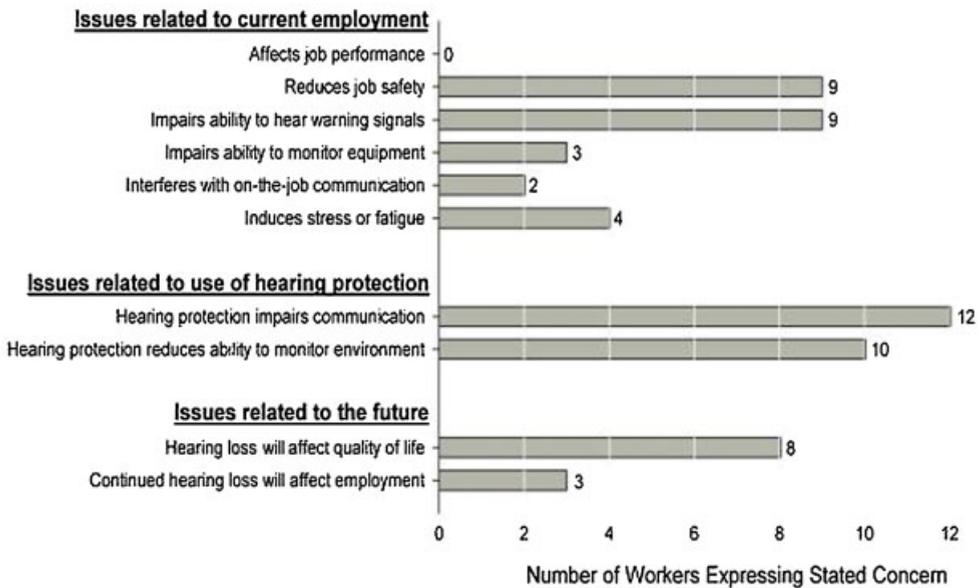


Figure 1 Difficulties and concerns expressed by noise-exposed, hearing-impaired workers and frequency of their expression during focus group sessions (reprinted from Morata et al¹⁹⁹). There were a total of 31 workers in the focus groups.

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 Australia²⁰¹ and the European Union²⁰² 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 Shield²⁰² estimated the overall cost of hearing loss in the European Union (including both economic and social costs) to be €224 billion euro in 2004. Ruben²⁰³ 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 colleagues¹³⁶ 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 al²¹¹ 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 Horwitz²⁰⁶ reported that the average cost per claim for NIHL in Oregon increased from \$3699 between 1984 and 1989 to \$6705 be-

tween 1990 and 1998. In Washington State, Daniell and colleagues¹³⁶ 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 colleagues²⁰⁰ 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 al²⁰⁴ 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 colleagues²¹³ 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. Ruttenberg²¹⁴ 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, Ruttenberg²¹⁴ 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 colleagues²¹⁹ 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 Praag²²¹ 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.

Ruttenberg²¹⁴ 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, Franks²²² 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 in-

crease 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 workers²²³ 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 al¹⁹⁹ 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 al²²⁷ 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 al²³³ 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 Suter²³⁴).

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 Systems⁹). 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 \sim 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 \sim 30 dB at 2000-, 3000-, and 4000-Hz frequencies or when the environmental noise levels fall below \sim 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 Paik²⁴⁴ 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 al²⁴⁷ 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 al²⁵³ 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 al²⁵⁵ 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 Yantek²⁵⁶ 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 colleagues²⁶⁴ 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. Begines²⁶⁵ 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 Axelsson²⁶⁷ 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 Kieper²⁷⁶ 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 neurosci-

ence 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 al²⁸⁸), asking subjects to rate statements about the effect of tinnitus on their lives.

Treatment involves mainly counseling, sound therapies, and medication (see Dobie²⁸⁹). 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 anti-hyperlipidemic 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 tinnitus³⁰⁴ 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 Sandridge³⁰⁶). 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 al²³⁵). Rovekamp³⁰⁹ 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 colleagues³¹⁰ 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 al³¹⁷). 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, Babisch³¹⁸ 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 al³¹⁹ 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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National Research Agenda for the Prevention of Occupational Hearing Loss—Part 2

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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) is tasked with generating new knowledge in the field of occupational safety and health and transferring that knowledge into practice for the betterment of workers. In 1996, NIOSH established the National Occupational Research Agenda (NORA), which identified occupational hearing loss as a priority research area. The NORA Hearing Loss Team, composed of representatives from industry, academia, labor, professional organizations, and other governmental agencies, has developed a national research agenda for the prevention of occupational hearing loss. This is Part 2 of that document, outlining research needed to address the problem through effective prevention programs.

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

ADDRESSING THE PROBLEM

Although there are many unanswered questions regarding the nature and scope of occupational hearing loss, it is not necessary to resolve all of them before acting to reduce the problem. In fact, from a certain standpoint, addressing the problem is especially important because it can have an immediate impact on reducing the incidence of occupational hearing loss. In reality, of course, these two arms of research must be accomplished simultaneously, the former informing the latter and the latter providing feedback to the former.

Traditionally, the occupational noise problem has been addressed through the establishment of effective hearing loss prevention programs (HLPPs). These programs typically involve seven components: noise measurement (to identify persons at risk), noise control (to remove the hazard insofar as possible), hearing protection (to prevent hearing loss when noise levels cannot be sufficiently reduced), audiometric monitoring (to ensure that protective measures are adequate), training and motivation (to encourage workers to engage in protective behaviors), record keeping (to permit

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evaluation of successes and failures), and program evaluation (to identify and correct program weaknesses). This section of the white paper focuses on each of these components in turn, describing what has worked, what might work even better, and what questions need to be answered to develop more effective approaches to hearing loss prevention.

In addition, this section identifies unique populations with special hearing loss prevention needs and discusses research that would enable these groups to be better protected against occupational hearing loss. This section also addresses treatment and rehabilitation issues for the many workers who have already sustained a work-related hearing impairment. Finally, the need to take hearing loss prevention beyond the occupational arena and into the overall public health arena is discussed.

In the past, National Institute for Occupational Safety and Health (NIOSH) research has focused primarily on noise as the problematic exposure and hearing loss as the preventable outcome. However, exposure to ototoxic chemicals and outcomes such as tinnitus and various other adverse effects of noise have gained prominence in recent years. Although these additional exposures and effects are discussed in this document and related research has been recommended, most of the measures integral to programs for prevention of hearing loss—in particular, engineering controls—could be expected to reduce the likelihood of these other adverse effects as well. In some cases, however, care must be taken that reducing one exposure does not increase another.

Noise Measurement

Learning Outcomes: As a result of this activity, the participant will be able to describe the different approaches to measuring worker noise exposure and their suitability for various applications.

Noise measurement is an essential component of many hearing loss prevention activities. Reliable and accurate noise assessments are necessary for:

- Identification of workers at risk
- Determination of noise sources significantly contributing to worker exposures
- Prioritization of engineering control efforts
- Application of appropriate intervention strategies
- Selection of adequate hearing protection devices (HPDs)
- Investigation of potential safety hazards (e.g., audibility of acoustic warning signals or communication systems)
- Evaluation of the success of noise controls and other intervention efforts
- Comparison of exposure data across time¹

Several approaches are available for noise measurement. However, the relative suitability (including cost-effectiveness) of each method for the various purposes listed above has not been studied.

The most routinely used method of noise exposure assessment is measurement of sound pressure levels, which may then be used to calculate dose. For occupational applications, sound-level measurements are usually made on an A-weighted scale, although linear measurements or other weighting networks may be indicated in certain situations. Calculation of dose involves specification of a threshold level, exchange rate, criterion level, and time; the dose calculation can vary considerably, depending on these parameters. A dose greater than unity (i.e., 100%) indicates overexposure according to the specified criteria. Dose may be measured directly with a dosimeter, or it may be estimated from various sound pressure level measurements and the amount of time a worker is exposed to each level.

Stephenson employed the Task-Based Exposure Assessment Model to apply the latter approach.² He developed a hazardous task inventory of activities associated with residential and commercial construction, from which he could estimate carpenters' noise exposures. Task-based methods offer several advantages over full-shift dosimetry measures, including measurement efficiency, evaluation of the contribution of individual tasks to the overall noise dose, and modeling the potential changes in exposure that would result from various administrative and engineering control options.³ In addition, the task-based approach offers the possibility of determining potential exposures on the basis of a central repository of noise measurements associated with a particular piece of equipment or job task. However, few studies have assessed the comparability of full-shift dosimetry measures and task-based exposure estimates. Seixas and colleagues³ found poor correlation between dosimetry and task-based measures in noise surveys of construction workers. They noted, however, a trade-off between the specificity of the task definition and random error. The more specifically the task is defined, the better will be the agreement with the full-shift measure, but the more difficult it will be to see contrasts between exposure groups. In addition, detailed task definitions may not be practically feasible. Smith et al⁴ further pointed out that task-based approaches are most accurate when the within-task variability is substantially smaller than the between-task variability; when this is not the case, exposure estimates are biased. Nonetheless, in view of the many advantages to the task-based approach, the development of more robust analytical strategies to overcome these difficulties is certainly warranted.

The accuracy of a particular exposure measurement in representing a worker's true exposure is an important question. The distribution of true daily noise exposures is dominated by the

day-to-day fluctuations. Many variables account for these differences, such as these:

- Worker mobility and/or rotation
- Changes in production volume
- Varying time spent at various tasks on different days
- Nonroutine, nonscheduled tasks
- Routine tasks conducted infrequently⁵

Reducing or eliminating these sources of variability improves the accuracy of the noise exposure assessment, ultimately improving the ability to appropriately protect the worker.

One nontraditional approach relates to the measurement of noise exposure beneath any protective device. A novel tool designed recently in an effort to reduce the variability introduced by hearing protection, which provides unpredictable attenuation under most field conditions, is the Quiet Dose Exposure Smart Protector (ESP) developed by Burks and Michael.⁵ The ESP incorporates a microphone in the hearing protector that measures sound levels under the protector throughout the workday and sends the data to a personal noise dosimeter. The dosimeter has warning lights that notify the worker if he or she is approaching the daily noise limit or if the level under the protector exceeds 85 dBA. At the end of the shift, the dosimeter displays the worker's "protected" daily dose, providing immediate feedback on the worker's protective efforts. The ESP has been evaluated by the manufacturer but, as of the time of this writing, no independent assessments have been published in the peer-reviewed literature. This promising technique warrants further evaluation.

One source of error with this kind of device would be the placement of the exterior microphone. A study by NIOSH addressed this issue by the simultaneous examination of eight microphone positions in the diffuse field as well as the direct field and comparing them to measurements made with a precision microphone.⁶ The results showed relatively minor errors due to dosimeter microphone placement in most of the diffuse-field positions. However, direct-field placement effects were large, depending on such factors as the microphone position, sound source location, and noise spectrum. The authors concluded that additional research is

needed to offset errors associated with the use of nonprecision microphones.

Another nontraditional approach to noise measurement is identification of postexposure temporary threshold shifts (TTSs). This technique offers the advantage of evaluating the effect of a given exposure on a particular worker, removing the significant variability of exposure effects across individuals. However, as discussed in Part 1 ("Mechanisms of Noise-Induced Hearing Loss" (pgs. 165–167) and "Factors Influencing Susceptibility" (pgs. 168–170)), recent evidence indicates that TTSs and permanent thresholds shifts (PTSs) are caused by different physiological processes.^{7,8} Thus, this measure may have little practical utility.

Extended work shifts are another area in which research has been scarce and assessment methods are poorly developed. Other than a few long-duration human noise exposure studies conducted by the military,^{9–11} there are few guidelines or standards that account for extended shifts. The general policy followed by the American Conference of Governmental Industrial Hygienists (ACGIH) allows for daily noise doses in excess of unity, provided that no daily dose exceeds 300% and the total dose over 7 consecutive days does not exceed 500%.¹² This is in contrast to the Occupational Safety and Health Administration (OSHA) noise regulation, however, which refers to the daily average noise dose based on an 8-hour day. The allowable durations of extended exposures are reduced accordingly. Documentation of the effects of extended exposures on hearing is needed, as are empirical data supporting these guidelines.

Appropriate methods for measuring infrasound and ultrasound are also needed. Many pieces of industrial equipment produce infrasound,^{13,14} and A-weighted measurements are not appropriate for characterizing these sounds.¹⁵ There is no U.S. standard for measuring infrasound; ISO 7196:1995(E)-Acoustics¹⁶ defines a G-weighting network for infrasonic measurements, but this standard rarely has been applied in U.S. occupational environments. The ACGIH publishes recommended limits for ultrasound, which it states can be measured with sound level meters with slow detection, one-third octave band filters and an appropriate frequency response. Studies

verifying the adequacy of these measures are warranted. Finally, development of a practical means to evaluate the effects of exposure to mixed sounds (continuous, intermittent, impulsive, infrasonic, and ultrasonic) would simplify occupational assessment.

RESEARCH NEEDS

- Build a matrix of noise measurement situations and appropriate, cost-effective measurement techniques.
- Develop analytical methods to maximize the utility of task-based exposure measurements by minimizing errors from within-task variability and lack of task specificity.
- Evaluate the need for special measurement approaches for nontraditional work shifts and infrasonic/ultrasonic noise.

Noise Control

Learning Outcomes: As a result of this activity, the participant will be able to discuss the importance of reducing noise at its source, describe misperceptions that create barriers to noise control efforts, and identify crucial factors that support successful control of noise.

The ultimate solution to noise-induced hearing loss (NIHL) is elimination of the noise exposures that cause such loss. Control technologies consist of engineering or administrative strategies that reduce excessive exposure to noise. In the hierarchy of control solutions, engineering controls hold the primary place because they reduce or eliminate hazards at a collective level rather than an individual level.¹⁷ Noise control predictably affects the environment of all persons in the area, whereas personal protective solutions perform variably across workers. The OSHA noise standard dictates that noise controls should be the first line of defense against excessive noise exposures.¹⁸ However, subsequent guidance provided in the OSHA technical manual states that enforcement of noise controls need not be considered when unprotected exposures are below 100 dBA and protected exposures can be demonstrated to be less than the permissible exposure limit (PEL).¹⁹ This has resulted in an unfortunate lack of emphasis on engineering control of occupational noise.

Several studies have indicated that engineering control of noise is both technically and economically feasible in most situations.^{20–22} Reducing noise levels by just 5 to 10 dB would be sufficient to bring nearly 99% of workers within the OSHA PEL.^{20,23} A decade ago, a conference on workplace controls reached the consensus²⁴ that proven technology exists and is readily available to control worker exposure to hazardous noise. However, noise control solutions are insufficiently implemented in the workplace.²⁵ Barriers to the implementation of noise control solutions must be identified and addressed.²⁶

Perhaps the most common barrier is the misperception that noise control is too difficult, too expensive, or not necessary if personal protective equipment is available. Contributing to this misunderstanding is a lack of coordinated dissemination of noise control information. Although many evaluations and case studies of noise control solutions have been published in

the professional literature, there is no central repository of searchable information readily available to work site personnel. As a result, the range of available solutions is wider than what is actually implemented.¹⁷ Documents such as the *Industrial Noise Control Manual*²⁷ and *Compendium of Materials for Noise Control*²⁸ have not been updated in nearly 30 years. NIOSH is in the process of revising these documents and making them available on the Internet. It should be mentioned that there are other documents available especially for the mining industry, such as *Noise Control in Underground Metal Mining*,²⁹ that provide the basic principles of noise control. Collection and dissemination of real-world examples of noise control, such as those published by WorkSafe Australia³⁰ and the European Agency for Safety and Health at Work,³¹ would be very useful.

Asawarungsaengkul and colleagues^{32,33} have developed a series of algorithms that companies could readily implement to determine the most effective noise control approach within budget and staffing constraints. Aluclu et al³⁴ have proposed a fuzzy logic model (i.e., a system based on approximate rather than precise values), which simplifies mathematical calculations for estimating the effect of proposed noise control treatments. Several software programs (e.g., Comprehensive Engineering Control Software, by Causal Systems Pty Ltd.; Environmental Noise Model, by RTA Technology; and SoundPLAN, by Braunstein + Berndt GmbH) have been marketed to assist in modeling appropriate noise control solutions. These tools could guide those responsible for compliance through the intricacies of identifying, selecting, and implementing engineering noise controls. However, all of them need to be evaluated and tested in real-world situations.

There are also gaps in control technology that need to be identified and addressed. One such gap is in the control of infrasound, which is poorly attenuated by barriers and can be carried across long distances.³⁵ Other technology gaps

that are barriers to the development of quiet machines and processes or that are necessary to enhance the technical/cost-effectiveness of a current control technology must be ascertained and solved.

Furthermore, development of appropriate mechanisms for dissemination of noise control tools and information is key. To date, knowledge transfer mechanisms have not been effective in getting noise control resources into the hands of those who need to implement them. A sector-by-sector approach has been suggested as the most efficient means to deliver information to each branch of industry,¹⁷ but the specific means of accomplishing this remains to be determined.

Another significant barrier to reducing noise is the lack of clear, correct, comprehensible noise emission information for equipment. In Europe, the Blue Angel labeling program (http://www.blauer-engel.de/en/blauer_engel/index.php) has assisted buyers in identifying quiet equipment. NIOSH has developed an Internet-accessible power tools database (<http://wwwn.cdc.gov/niosh-sound-vibration/>) that enables companies and consumers to compare noise emissions across equipment. Expansion of initiatives such as these, as well as evaluation of their effectiveness, is warranted.

Lack of trained acoustical engineers is also a barrier to accomplishing the extent of noise control needed in industry. The serious lack of academic training programs in acoustics has resulted in engineers graduating with little or no knowledge regarding noise control. Dissemination of existing noise control information, as noted earlier, would also facilitate incorporation of noise abatement techniques into engineering training programs, as well as assist current engineers who are assigned engineering noise control responsibilities.

Although noise control in industrial environments has not been as widely implemented as it could be, successes in other venues can serve as a guide. Aviation, defense, and mining have all achieved substantial success in reducing noise levels. Bruce and Wood²⁵ attribute these accomplishments to the following crucial factors:

- Recognition of the need for control, based on the prevalence of NIHL

- Established technologies for reducing noise
- Political will to reduce noise levels
- Demonstration of successful solutions
- Collaboration across interested parties (government, industry, etc.)

Several of these components for success already exist in the industrial sector. Efforts to increase recognition of the need to improve collaboration for disseminating knowledge are necessary to achieve similar success in reducing occupational noise levels. Research that identifies methods to accomplish this is sorely needed.

Finally, we know that using tools and machinery that produce less noise will help prevent hearing loss among the workers who use them. Currently, the availability of quieter tools and machines is limited, and it is not always clear to purchasers how much noise particular tools and machinery produce. NIOSH, the National Aeronautics and Space Administration, and the Department of Defense are working to develop effective “buy quiet” and “quiet-by-design” programs that can help businesses and end users make good decisions about purchasing quieter tools and equipment. More research is needed on how to stimulate the manufacturing, labeling, and application of quieter tools and equipment.

RESEARCH NEEDS

- Compile an updatable best practices reference and case study series.
- Develop an acoustical materials compendium of existing, proven control technologies.
- Determine effective knowledge transfer mechanisms to get usable noise control information to implementers at work sites.
- Conduct research/demonstration projects to fill technology gaps and to evaluate new and emerging technology.
- Develop additional training opportunities in acoustical engineering to increase the availability of noise control expertise.
- Support translational research on methods to stimulate the manufacture, labeling, and use of quiet tools and equipment.

Hearing Protection Devices

Learning Outcomes: As a result of this activity, the participant will be able to explain the various methods for evaluating hearing protector performance and identify the factors that influence hearing protector effectiveness.

HPDs control noise at the receiver by blocking the path to the ear. Although reducing noise at its source is preferable, hearing protectors may be necessary when engineering controls are infeasible or insufficient to bring noise down to a safe level. When properly selected, fit, and worn, HPDs can successfully prevent NIHL. Three primary factors influence the effectiveness of hearing protection: the potential attenuation of the device, the adequacy of its fit, and the proportion of time it is worn.

Historically, protector attenuation has been measured in terms of real-ear attenuation at threshold (REAT), which is the difference between the occluded and unoccluded audiometric thresholds. In the United States, federal regulations issued by the Environmental Protection Agency (EPA) mandate that hearing protectors be labeled with a Noise Reduction Rating (NRR), which is an index derived from REAT measures (40 CFR Part 211). The NRR was designed to predict the amount of protection 98% of wearers would achieve if the devices were ideally fit and worn.³⁶ However, research has shown that fewer than 5% of workers actually receive the protection predicted by the NRR.³⁷ OSHA³⁸ and NIOSH³⁹ have proposed various NRR derating schemes to adjust for this. However, even derated NRRs do not correlate well with real-world performance.⁴⁰ HPDs with more highly labeled NRRs do not necessarily provide more protection than HPDs with lower NRRs.

The American National Standards Institute (ANSI) standard for testing the attenuation of HPDs, ANSI S12.6, was revised in 2008 and describes two protocols for measuring REAT based upon either an experimenter-trained subject fit procedure or an inexperienced subject fit procedure (Methods A and B, respectively).⁴¹ The 2008 revisions to ANSI S12.6 were designed to facilitate testing hearing protectors in a manner that better predicts real-

world hearing protection. Although it is still based on REAT measures, the revised standard utilizes two somewhat different protocols (Methods A and B), in which the subject rather than the experimenter fits the hearing protector for testing. The EPA⁴² has proposed a revised hearing protector labeling regulation, and a final regulation should be promulgated shortly. The proposal's testing methods and rating scheme for the new NRR are based on Method A of ANSI S12.6–2008, and instead of a single number NRR, a range of values would be specified. The proposed rating methods will apply to many types of devices, such as custom-molded protectors, sound restoration devices, communication headsets, and active noise reduction devices. For example, the new proposal provides for microphone in real ear (MIRE) and acoustic test fixture methods to evaluate active noise reduction and impulse noise reduction. Consequently, the ANSI standard has been revised to be compatible with the EPA proposed rule (ANSI S12.42–2010).

REAT measures have several limitations that are not addressed by ANSI S12.6–2008. The technique is not appropriate for level-dependent hearing protectors, which provide varying degrees of attenuation according to the noise level. REAT measures have also not been standardized for use with impulsive noise. The MIRE technique overcomes this problem by objectively measuring the sound level in the ear canal, with and without the protector. However, placing a microphone in the ear canal under a protector opens a small path for possible sound leakage, which can introduce inaccuracies into the measurement. In addition, MIRE testing does not account for bone conduction transmission or the occlusion effect produced by physiological masking.⁴³ Alternatively, MIRE measurements can be performed with use of an acoustic test fixture in which the microphone is placed inside the “head” of the acoustic test

fixture. Lack of an acoustic test fixture that exactly replicates the acoustic characteristics of the human head and ear has hindered certain aspects of hearing protector research.⁴⁴ However, the system specified in ANSI S12.42–2010 should facilitate additional research to develop and validate hearing protector test methods that can be used across various types of protectors and noise signals.

The second factor influencing hearing protector effectiveness is the adequacy of fit. The hearing protection testing methods described do not predict the performance of a particular device on a particular individual, which can vary considerably. In fact, many workers have been shown to obtain only a fraction of an HPD's labeled attenuation as the HPD is worn in the workplace. Furthermore, even after having been trained, a worker is still likely to achieve only a fraction of the labeled protection.^{45,46} Thus, fit-testing is a mechanism that can be used to provide feedback and thereby improve the amount of attenuation a given user can achieve.

Unlike respirators, there has been no requirement to fit-test hearing protectors. Undoubtedly, this has been because of the lack of methods and instruments to conduct individual fit tests. Recently, however, this has changed. Currently, there is a variety of commercially available hearing protector fit-test systems, and new systems are regularly appearing in the marketplace. As a result, more hearing conservation programs are including fit-testing. Recently, NIOSH, OSHA, and the National Hearing Conservation Association (NHCA) entered into an alliance focused on preventing occupational hearing loss. This alliance issued a position statement⁴⁷ that recommended routine hearing protector fit-testing.

Each fit-test system has its own unique advantages and disadvantages, and one must be chosen according to the needs of a hearing conservation program. Nevertheless, all fit-test systems can yield valuable information on the attenuation a worker is receiving at a given moment, and they can be very useful as training tools. However, the extent to which the individual test results can be generalized to the worker's in situ and/or habitual use remains to

be demonstrated. Their validity would be improved with repeat testing, and in some cases their use needs to be simplified and made more practical. Because HPD fit-testing represents a relatively new phenomenon, practical research and evaluation are needed.

The third factor influencing protector effectiveness is the proportion of the time it is worn. A hearing protector with an NRR of 30 that is removed for 10% of an 8-hour shift is reduced to an effective attenuation of less than 10 dB.⁴⁸

Selection of appropriate HPDs has tended to focus primarily on the attenuation properties of the protector, with scant attention to other factors that influence adequacy of fit or consistency of use. It is generally assumed that protectors with higher laboratory ratings are better HPDs, but this assumption is faulty. Ninety percent of occupational noise exposures are at or below 95 dBA. Most hearing protectors are capable of producing the 5- to 10-dB attenuation necessary to reduce exposure to 85 dBA or lower.⁴⁹ Hearing protectors should not reduce noise to below 70 dBA (European Standard EN 458⁵⁰), because overprotection can cause workers to feel isolated from their environment and may impede communication, leading to removal of the protectors.⁵¹ Giguère et al⁵² have contributed to the cause of appropriate HPD selection by developing and validating a model to predict speech perception in noise for hearing-impaired individuals using HPDs. They found that accurate predictions for the protected condition depended upon both audibility (threshold) and distortion (suprathreshold) corrections. Strategies are needed to persuade hearing conservationists and HPD manufacturers to shift away from an attenuation-driven approach and to adequately consider factors such as comfort, compatibility, communication, signal detection, durability, and maintenance.⁴⁸

Hearing protector comfort is a neglected feature that deserves attention, because the wearability of an HPD may be the single most important factor in the consistency of its use. Davis⁵³ recently reviewed existing research on hearing protector comfort. Studies indicate that short-term comfort tests are predictive of long-term comfort, at least for earmuffs.^{54,55}

There was wide variability across studies regarding which factors correlate with comfort. However, Davis⁵³ showed that workers rate the comfort of their own HPDs and rank the comfort of other HPDs in a consistent manner. Therefore, further study of this issue—though subjective—is feasible and warranted.

A standardized comfort index would be helpful in comparing and selecting appropriate protection. Several approaches have been proposed and tested,^{55–60} but no metric has been universally adopted. A widely accepted comfort measure based on sufficient wearing time and experience, conditions as close as possible to work site conditions, and psychometric procedures would be a valuable adjunct to attenuation indices. This would facilitate the shift away from selecting protection exclusively on the basis of the NRR. It would also afford useful feedback for the design of future HPDs. The few studies that have already been accomplished have provided important information regarding what aspects of hearing protector design are critical for comfort and wearability.^{60,61}

Emerging technical advances in electronics must continue to be evaluated with regard to their utility for improving personal hearing protectors. Recent work in active noise reduction algorithms has shown promise in increasing the amount of potential noise cancellation possibilities.^{62,63} Hearing aid signal processing algorithms such as adaptive multichannel modulation-based noise reduc-

tion and multichannel dynamic range compression have been shown to improve noise reduction and increase sound quality in hearing protective applications. Other hearing aid technologies such as directional microphones and automatic telecoil switches may have potential for enhancing noise reduction, speech intelligibility, and localization ability.⁶⁴ Noise cancellation, adaptive networks, and voice-enhancing circuitry all require continual application to the problem.

RESEARCH NEEDS

- Evaluate the relevance of revised labeling requirements for predicting real-world performance of HPDs, especially level-dependent and other nonstandard hearing protectors.
- Refine field-based evaluation tools that allow an individual to quickly and easily determine the personal performance of a protector.
- Develop, validate, and employ a comfort index for hearing protectors.
- Design strategies to promote the selection of personal HPDs according to wearer comfort and enhanced speech understanding rather than attenuation alone.
- Apply new and existing technologies to enhance communication, localization, and other important hearing functions while wearing HPDs.

Audiometric Monitoring

Learning Outcomes: As a result of this activity, the participant will be able to discuss the purpose of audiometric monitoring in noise-exposed populations and current issues that are being considered to make such monitoring more effective.

Hearing loss due to chronic noise exposure develops slowly and insidiously over time, providing little warning of its occurrence. Ideally, prevention of occupational NIHL involves identification of workers at risk for threshold shifts before permanent hearing loss occurs. Traditionally, this has been done by conducting periodic hearing tests and comparing the results to baseline thresholds. However, too often, audiometric monitoring serves only to document hearing shifts after they take place. It would be useful to develop audiometric indicators that would identify employees who might be susceptible to NIHL or with early signs of potential hearing damage so that interventions could be initiated before the damage becomes permanent.

Pure-tone audiometric techniques were developed in the 1940s on the basis of electronics and psychophysical theories of the time.⁶⁵ The use of a 5-dB step size in pure-tone threshold testing provided reasonable accuracy and repeatability in the days of vacuum tube audiometers and manual testing. Although current electronics and calibration instruments permit much greater accuracy in test signals, testing techniques have remained largely unchanged. Long-used test protocols may not be adequate for occupational hearing testing, which requires the identification of relatively small changes in hearing.

Automated testing techniques that are more efficient and precise have been developed in the laboratory.^{66–70} The feasibility of these techniques for testing the wide variety of noise-exposed workers is promising, but their effectiveness and practicality remain to be thoroughly investigated in the field. Increasing the precision and accuracy of threshold estimation and reducing test-retest variability could potentially provide more sensitive means of identifying the onset of individual hearing loss and of assessing the effectiveness of hearing conservation programs.

Because TTSs are indicative of overexposure, NIOSH and other professional organizations have advocated conducting periodic (most commonly, annual) audiometric monitoring during or after the work shift.^{39,71,72} Theoretically, identification of a TTS would permit worker protection to be increased so that permanent threshold shifts would not develop or progress. However, the efficacy of this procedure in preventing NIHL has yet to be validated, and recent research has indicated that the mechanisms of TTSs and PTSs may differ.^{7,8} As discussed in Part 1 (under “Mechanisms of Noise-Induced Hearing Loss” (pgs. 165–167)), there is evidence, at least in animal models, that neurological damage may occur even in cases in which recovery from a TTS is complete.⁷³ However, the TTS should not be dismissed as a training tool in the absence of further evaluation. Studies are needed to examine the rates of permanent threshold shifts in programs that test hearing during or after the work shift versus those that conduct audiometric monitoring prior to the daily noise exposure.

Testing conditions also have a major effect on test results. OSHA regulations permit hearing testing in ambient noise levels that far exceed the ANSI maximum permissible background noise levels for clinical audiometric evaluations. Studies have shown that it is not always possible to obtain accurate thresholds in an ambient noise level as high as that permitted by OSHA.⁷⁴ However, levels that meet the current ANSI standard for ambient noise were not considered feasible for industrial audiometry when the current version of the OSHA regulation was promulgated.¹⁸ More recent research has indicated that most industrial test facilities come very close to meeting the ANSI standard except at 500 Hz, a frequency that is not critical for monitoring NIHL.^{75–77}

Insert earphones would be helpful in solving the ambient noise problems with industrial audiometry, but their use is almost exclusively

confined to audiology clinics. A recent study by Bell-Lehmkuhler et al⁷⁸ indicated that occupational hearing conservationists could be successfully trained to use insert earphones, at least in a quiet environment, but these issues need to be further explored in the field. In addition, the ruggedness of insert earphones in mobile environments and the reliability of daily bioacoustic calibration procedures need to be evaluated before these earphones can be put into widespread use for occupational audiometric testing.

Extraneous noise can also be problematic during a test, particularly when multiple persons are tested simultaneously. The ability of the listener to distinguish the test signals from extraneous sounds and the impact such distractions have on test reliability have not been evaluated. It would be helpful to determine whether the size of the group tested adversely affects results and whether there is an optimal group size that limits variability while maximizing resource expenditure.

The scheduling paradigm for audiometric testing is another important issue. OSHA regulations currently permit obtaining a baseline audiogram up to 1 year after employment begins. Additional research would be of benefit in determining the time period that should not be exceeded to identify early NIHLs. In addition, workers are required to have monitoring exams annually, regardless of their exposure levels or hearing history. Perhaps it would be more effective to vary the monitoring interval according to a worker's level of exposure and prior threshold stability. The impact of a varied monitoring schedule on identification of early threshold shifts, overall cost of HLPPs, and other factors such as training (which is often conducted in conjunction with the annual audiogram) should be considered.

The definition of hearing threshold shift could also benefit from continued research. Although the OSHA regulation uses an average shift of 10 dB or more at 2000, 3000, and 4000 Hz as an indicator of significant hearing change (a "standard threshold shift," or STS), other criteria have been proposed and studied. In developing the revised NIOSH document *Criteria for a Recommended Standard: Occupational Noise Exposure*,³⁹ eight different threshold shift criteria were evaluated. NIOSH

published the relative merits of each criterion, noting that no definition was best in every respect. NIOSH did note, however, that criteria that make use of averaged thresholds are less sensitive than criteria based on threshold shifts at a single frequency. Rabinowitz et al⁷⁹ recently published an analysis of 12 different examples of threshold shift criteria, which they called "early flags" for occupational hearing loss. The investigators attempted to find a metric that would maximize the time between early identification and a hearing loss great enough to be recorded on the OSHA 300 log, while at the same time minimizing false-positive identifications. The results indicated that a 10-dB non-age-corrected shift at 2, 3, and 4 kHz, or an 8-dB age-corrected shift at these same frequencies, best met these criteria.⁷⁹ Unfortunately, the authors did not include the presence of tinnitus as a potential "early flag." Continuing research is needed to select criteria that can identify incipient NIHLs without an inordinate loss of sensitivity.

The current process for determining the presence of an STS allows for the use of an age-correction procedure. The purpose for age-correcting audiograms is to prevent employers from being held responsible for hearing changes due to aging rather than noise exposure. However, because age-correction data are derived from studies of large populations, it is statistically inappropriate to compare individual data to population data. In addition, as described above, age corrections can sometimes mask early signs of noise-induced threshold shift.⁷⁹ The OSHA age-correction tables, which were derived from the original 1972 NIOSH criteria document on noise exposure, have some potential problems as well. Correction factors are supplied only through age 60, although the prevalence of older persons in the workforce is increasing.⁸⁰ The tables also do not distinguish among various racial/ethnic groups, although data suggest that susceptibility to hearing loss varies across various race/ethnicities.⁸¹

Since publication of the original NIOSH noise exposure data,⁸² more recent normative data have become available. Hoffman et al⁸³ analyzed data from the National Health and Nutrition Examination Survey and found hearing threshold levels in a large sample of the U.S. population that were somewhat lower (better)

than those usually used for damage-risk criteria in Annex B of ANSI S3.44, at least for the frequencies 0.5, 3, 4, and 6 kHz. In an analysis of data from the Baltimore Longitudinal Study of Aging, Pearson et al⁸⁴ found even lower thresholds in their cohort and provided additional data for the age groups of 60 to 69 and 70 to 79 years. If regulators and employers persist in the use of age corrections, then current, representative, nonoccupationally noise-exposed models need to be utilized. In addition, more research is needed to determine appropriate methods for distinguishing age-related hearing loss from that induced by noise, while still providing the earliest possible indication that noise is affecting a worker's thresholds.

Another issue involves the definition of hearing impairment with respect to recording hearing shifts for the purpose of surveillance or regulatory compliance. The current OSHA requirement is that hearing threshold levels must exceed an average of 25 dB in the frequencies 2000, 3000, and 4000 Hz before an STS is considered recordable.⁸⁵ Because audiometric zero is actually an average value and some members of the population will have exceptionally good hearing, it is possible that a person who enters the workforce can have average thresholds, for example, of -10 dB. If this person suffers a threshold shift that exceeds the 25-dB criterion, he or she will have lost a considerable amount of hearing. The amount of hearing impairment leading to recordability and the basis for this decision needs to be reexamined. The impact of these and other, more severe hearing changes on the ability to process and respond to complex auditory signals such as warning sounds and speech in noise, reverberant environments, or other difficult listening situations has been extensively evaluated, but the results of these studies need to be applied to hearing conservation program practices.

Pure-tone air conduction thresholds have been the foundation of audiometric monitoring since the inception of hearing conservation programs. However, new test procedures are developing that may prove to be more sensitive measures of early NIHL. Otoacoustic emissions (OAEs), which appear to directly evaluate outer hair cell function, have been the subject of several studies. Though some results have indi-

cated that OAEs can detect preclinical changes in hearing due to noise exposure,⁸⁶⁻⁸⁸ other results have been less consistent.⁸⁹ In addition, differences across age^{90,91} and gender⁹² have been identified, differences that would need to be considered in using OAEs to monitor the effects of noise exposure on hearing. No clear consensus exists as to the type of emission (evoked or distortion product) or the measurement parameters that are most sensitive to noise-related changes. Furthermore, OAEs are a physiological, preneural measure of auditory function (akin to tympanometry in this sense) and thus do not evaluate the auditory system as a whole or hearing ability per se.⁹³ Nonetheless, continued research into the utility of OAEs in predicting NIHL and in identifying NIHL changes and the potential role this technique might play in audiometric monitoring is warranted.

A few other techniques may also show promise as a tool for monitoring NIHL. Certain parameters of the acoustic reflex may be indicators of noise damage.^{94,95} The utility of the auditory brain stem response in identifying early hearing changes due to ototoxic drugs^{96,97} suggests that auditory brain stem response might have similar utility in monitoring hearing changes due to ototoxic occupational exposures. Measures of speech intelligibility in noise also have potential for indicating both early stages of hearing loss and functional impairment in the workplace.^{52,98}

Finally, it is often the case that a professional reviewer of audiometric test results must make judgments and recommendations without having participated in the testing process. Studies to determine the accuracy of this disconnected procedure and to identify additional information that might be provided to the reviewer to facilitate the process are needed. One key aspect that is useful in reviewing audiograms could be the noise notch. Currently, there is no consensus on the definition of the notch, although criteria have been proposed by Coles et al,⁹⁹ Niskar et al,¹⁰⁰ Rabinowitz et al,¹⁰¹ and Hoffman et al.¹⁰² A recent examination of four definitions of the noise notch in a large population of adults aged 48 to 92 revealed significant disagreements among the four algorithms and a substantial portion of the non-

noise-exposed population exhibiting notches. The authors conclude that although an objective definition of the noise notch would be helpful, audiometric shape does not appear to be a clear indication of the etiological pathway.¹⁰³ Furthermore, there is increasing evidence that the notch may initially present at 6000 Hz rather than 4000 Hz as traditionally thought,^{104,105} although some have attributed this to an inaccurate reference value for audiometric zero.¹⁰⁶ If a notch truly is present at 6000 Hz, reviewers will not be able to identify it unless 8000 Hz is included as a test frequency.

RESEARCH NEEDS

- Develop refined pure-tone audiometric techniques with less variability and more sensitivity to early noise damage.
- Investigate the impact of test conditions, particularly ambient noise levels and multiple subject testing situations, on threshold measurements.
- Explore the use of insert earphones in the occupational setting, including issues surrounding calibration and reliability.
- Determine the most efficient and sensitive testing interval for exposed workers.
- Develop better definitions of significant threshold shift, designed to identify the earliest possible signs of NIHL.
- Develop tools for professional reviewers that would better enable them to assess work relatedness and the need for follow-up actions. Reevaluate the use of age corrections and develop updated tables with extended ages and accounting for race/ethnicity if appropriate.
- Evaluate the potential of other, more sensitive tests for predicting, identifying, and monitoring NIHL.
- Determine the most efficient test frequencies for use in periodic audiometric monitoring for occupational hearing loss.

Training and Motivation

Learning Outcomes: As a result of this activity, the participant will be able to recall important factors that influence the success of the education and training elements in a hearing loss prevention program.

Education and training elements have always been a part of hearing loss prevention programs. However, the effectiveness of training and motivational programs in forming consistent behaviors that reduce or eliminate the incidence of occupational NIHL has seldom been evaluated; among the studies that have been done, the evaluation methods and conclusions vary widely. The fact that occupational hearing loss continues to rank among the most common work-related injuries indicates that there is more work to be done in developing effective ways of communicating risk and prevention information that motivate workers and managers to take action.

Traditionally, worker hearing conservation training has involved didactic programs emphasizing gains in factual knowledge, such as the anatomy of the ear, the physics of sound, and the importance of wearing hearing protectors in noise. Hearing conservationists assumed that providing trainees with sufficient information would lead to the adoption of protective behaviors. However, studies have shown that even when workers exhibit increased knowledge regarding hazards, often only minimal, possibly short-term, positive changes are observed in their behavior.¹⁰⁷ Thus, lack of knowledge is not the only culprit contributing to the reluctance of workers to protect their hearing.¹⁰⁸⁻¹¹⁰

Popular models of health behavior, such as the Health Belief Model,¹¹¹ Health Promotion Model,¹¹² Theory of Reasoned Action,¹¹³ and Transtheoretical Model of Change,¹¹⁴ have been invoked to explain this phenomenon. These models tend to emphasize the characteristics and beliefs of an individual worker that set him or her apart from the workers who cooperate with and participate in safety directives. Although understanding individual differences in attitude, belief, and intention and recognizing stages of behavior change are useful, the person-centered models have not adequately incorporated many other factors now known to contribute to safe worker behavior.

Newer models of health behavior stress interdisciplinary viewpoints and contain parameters that focus on the interaction of environmental, psychological, and social determinants of behavior.^{115,116} These may include social factors (such as shared values and peer pressure), the cultural characteristics of the work environment (such as the general level of safety awareness and commitment within an organization), and aspects of the physical setting (such as the ease of obtaining protective equipment). In addition, both actual and perceived barriers are important issues influencing workplace safety and have often been the strongest predictors of workplace behavior.¹¹⁷ Studies of the impact of such social, cultural, and physical factors on hearing protective actions are important to developing more effective motivational strategies, and recent evidence suggests that using training materials based on a combination of health communication models may be the most effective way to positively influence attitudes, beliefs, and behavioral intentions.^{118,119}

Research has also suggested that training programs must frame messages appropriately for the particular audience.¹²⁰ Individuals have different learning styles, and their educational needs change as they progress through their working career. For example, workers who still have normal hearing require a different approach than workers who have already suffered a hearing loss.^{121,122} The age, gender, and racial/ethnic background of the workers can also influence the success or failure of a training approach.¹²³⁻¹²⁵ A "one size fits all" educational program in hearing loss prevention may not be feasible. Continued research into the effectiveness of various techniques among different populations is warranted.

Studies are needed to validate various training approaches that have been in common use or are generally considered effective. In many instances, recommendations have been based on little more than a single case study or

anecdotal evidence. In other cases, research has found mixed results, indicating perhaps that additional factors must be considered in implementing an effective training program. Although the efficacy of training programs is often measured with survey questionnaires, other approaches have also proved successful. Neitzel and his colleagues used dosimetry to collect noise measurements, along with activity cards on which workers could easily record their use (and nonuse) of HPDs.¹²⁶

Most reports suggest that it is more effective to integrate hearing health information into the overall health and safety program of the workplace.¹²⁷ An alternative strategy is to establish the hearing health program as a stand-alone effort outside of the general safety program. The relative effectiveness of these approaches in producing long-term behavior change has not been established. Situational variables that may affect the efficacy of one approach over the other should be identified.

Some hearing conservationists advocate rewarding workers for wearing personal hearing protectors and punishing those who do not. Classic behaviorist theory also suggests that initiating an incentive program to reinforce protective actions should be successful in shaping safe workplace behavior.¹²⁸ However, a strong body of research from the social sciences suggests this approach may be counterproductive in the long run.^{129,130} Parameters of successful incentive/disciplinary programs as well as unintended consequences associated with such programs specific to hearing loss prevention have not been defined.

Social modeling theory suggests that testimonials from respected peers and supervisors should be an effective educational approach.¹³¹ The credibility of the trainer is an important component of convincing an audience to change behavior. In recent years, several public figures—such as rock singers, race car drivers, and politicians—have discussed their hearing loss openly, but the effectiveness of this strategy has not been tested. The successful use of peer trainers has been demonstrated in some programs.^{126,132}

Another issue for further research is the role of personal responsibility versus workplace redesign in the establishment of effective mo-

tivational programs for hearing loss prevention. Some researchers suggest that the most effective way to ensure compliance with hearing protection requirements is through a safety culture that supports individual responsibility. Certainly, many studies support the importance of building workers' self-efficacy (i.e., their belief that they have the ability to take the necessary actions to protect their own health).^{133,134} Others have suggested that this approach can be corrupted and lead to a "blame the victim" mentality that is counterproductive to workplace safety.^{135,136} Rather than changing worker behavior to fit the workplace, they suggest redesigning the workplace to establish an infrastructure that enables individuals to engage in responsible behaviors.¹³⁷ Another successful approach is the "Dangerous Decibels" program developed at the Oregon Health & Science University, in Portland, for the school environment.¹³⁸⁻¹⁴³ Additional outcomes relating to a successful HLPP and behavioral interventions are available.^{144,145}

Some attempts at nontraditional interventions have yielded results. For example, postcards with positive, negative, or neutral messages were mailed to Appalachian coal miners, encouraging the use of HPDs on the job. The investigators found that positive or neutral messages were significantly more effective than the negative ones in the self-reported use of HPDs.¹⁴⁶ Because the study's validity may have been affected by the low response rate (28%), other such investigations could be beneficial. In an examination of several intervention studies to promote the use of HPDs, reviewers found only two studies meeting their criteria.* The intervention that proved most effective was a 4-year, school-based hearing loss prevention program for students working on family farms. The intervention group was twice as likely to use HPDs as the control group, which had received minimal training.¹⁴⁷

Another nontraditional program is the Safe-in-Sound Award for Excellence and Innovation in Hearing Loss Prevention (www.safeinsound.us), created by NIOSH in

* This was the first of two recent efforts by the Cochrane Collaboration¹⁴⁷ to evaluate interventions in hearing loss prevention programs.

partnership with the NHCA.¹⁴⁸ The purpose is to recognize organizations that document measurable achievements and to share their information and successes with a larger community. Recipients report on their experiences at the annual meeting of the NHCA.¹⁴⁹ These kinds of activities need to be replicated, supported, and publicized.

In recent years, joint labor-management teams that emphasize participatory decision making have become a popular approach to a variety of occupational issues, including health and safety. Hearing conservation program elements most amenable to the joint labor-management approach should be identified, and lessons learned should be publicized to guide new efforts.

Hearing conservationists have generally assumed that the best time to conduct hearing conservation training is during the worker's annual hearing test,^{71,127} although only a few studies have investigated this approach,¹⁵⁰⁻¹⁵² and one recent study has called it into question.¹⁵³ The OSHA requirement that training be conducted at least annually has often resulted in hearing conservation training being offered only once a year. One recent study¹⁵⁴ investigated the effect of periodic booster messages but found them ineffective and expensive. Research is needed to determine the optimal frequency and most effective timing of communications on hearing impairment and its prevention.

Perhaps one reason why training at the time of the annual audiogram is not as universally effective as might be expected is that small changes in hearing are not functionally meaningful to workers. Methods of demonstrating the impact of even small threshold shifts to workers are needed. Incorporating such methods into workplace training might enable workers to notice changes in their own hearing and seek out a hearing test before the annual exam if a shift is noted; this could decrease the intervention time for an employee whose hearing protection might be insufficient. In addition, methods enabling workers to conduct a quick and easy assessment of their temporary threshold shift following any type of noise exposure could also be effective. Studies are needed to assess the degree to which this would be a useful

motivational tool for those exposed to occupational noise.

Although many educational products and materials are available for use in training programs, few have been evaluated for efficacy. An important step in ensuring that training and motivational programs are effective would be to conduct studies of existing materials in view of contemporary knowledge of health promotion models and message framing. Development of new products incorporating health communication principles is also warranted and should take into account lessons learned from the evaluation of existing programs.

Training materials utilizing computer-based technologies have been evaluated in a few studies, with mixed results.^{155,156} The potential benefits of such technologies include the ability to tailor training to each worker's particular job, noise exposure, and personal interests. However, studies of the tailored approach (i.e., programs based on individual characteristics) versus the more traditional targeted approach (i.e., programs based on shared characteristics) have also yielded mixed results.^{114,156-158}

Whereas many training programs discuss the structure and function of the ear and the physiological mechanisms by which noise destroys hearing, few programs emphasize the critical importance of hearing to quality of life. The potential motivational value of effectively communicating quality-of-life issues to noise-exposed individuals should be evaluated. Materials that accurately depict the difficulty of understanding speech in background noise, the effect of lost or impaired frequencies on the appreciation of music or the sounds of nature, and the inability to hear safety or machine maintenance clues at work may be useful. Emerging technologies such as virtual reality might facilitate development of programs that utilize this type of experiential learning.¹⁵⁹

Additional information seldom discussed in worker training programs includes education for workers who have already sustained a hearing loss, regarding preservation of their remaining hearing, utilization of aids and other assistive devices, and successful accommodation strategies that will enable them to continue as safe,

productive employees. Training tools that encourage management to consistently model safe behavior are also scarce and could be beneficial.

Clearly, training and motivation programs must consist of more than showing a film and passing out a pamphlet. To be effective, it must communicate the value of healthy hearing. Training also must equip both workers and management so that they feel empowered to overcome barriers. Successes and failures should be widely disseminated so that all the variables affecting the outcomes of training and motivation can be identified and addressed.

RESEARCH NEEDS

- Define social, cultural, and physical factors that are important in motivating workers to practice hearing protective behaviors.
- Develop educational materials that can motivate decision makers to implement hearing loss prevention programs based on best practices.
- Validate various training approaches, including integration of hearing conservation training into an overall health promotion program, incentives/disincentives, testimonials, and periodic booster trainings.
- Investigate the best use of training time, in association with the annual hearing test or other specific times.
- Evaluate the efficacy of available training materials and identify strengths and weaknesses for consideration in developing new programs.
- Expand and investigate the utility of emerging technologies such as virtual reality in hearing loss prevention training.
- Further investigate certain nontraditional interventions and support and expand those that have proven effective.
- Investigate the utilization of the “Dangerous Decibels” program (HLPP) as used in schools for those transitioning from the educational environment to the work force and for those already in the work environment.

Special Populations

Learning Outcomes: As a result of this activity, the participant will be able to identify groups of workers who may require special efforts to ensure that they are protected from occupational hearing loss and describe strategies for reaching these vulnerable populations.

Certain populations provide special challenges for occupational hearing loss prevention. Some workers are considered vulnerable because of personal or cultural characteristics that make them less likely to engage in protective behaviors. Special efforts may be required for young workers, older workers, non-English-speaking workers, and hearing-impaired workers to ensure that they are properly trained regarding noise hazards, have appropriate hearing protective devices, and feel empowered to demand a work environment that does not pose a risk to their hearing. Other workers are considered vulnerable because they work in professions that are not easily amenable to standard hearing conservation practices. Creative, concerted efforts are required to ensure that temporary workers, mobile workers, and workers who are not covered by governmental noise regulations are as well protected as workers in stable, regulated work environments. Further research is needed on the best practices to protect these special worker populations.

Young Workers

Research indicates that 70 to 80% of teenagers work for pay at some time during their high school years.^{160,161} On average, 2.9 million youths aged 15 to 17 years work during school months and 4.0 million work during the summer months. The industries in which young workers are most commonly employed include several in which noise hazards may be present, such as farming, forestry, fishing, and construction.¹⁶² Young workers may be at increased risk of occupational hearing loss because of inexperience, unfamiliarity with worker protection laws and safe work practices, perceived lack of empowerment to refuse unsafe assignments, and a sense of invulnerability.^{162,163} In addition, youths are often employed on a part-time or temporary basis and may therefore be missed by workplace hearing conservation programs. Very

young children (e.g., on family farms) who have not yet reached physiological or biochemical maturity may have increased susceptibility to the effects of noise and other ototoxic agents.¹⁶⁴

Several studies have found evidence of early NIHL among youths, although no studies have specifically examined the contribution of employment to noise notches.^{100,165} Research regarding occupational hearing loss among young workers has focused primarily on farm youths and high school industrial shop students. Young adults actively involved in farm work have been found to have a higher prevalence of hearing loss than rural youths who do not work on farms,¹⁶⁶ and intervention programs targeting farm youths have been shown to be successful.¹⁶⁷ Noise levels in industrial shop classes have been measured as high as 110 dBA.¹⁶⁸⁻¹⁷⁰ A survey of vocational/technical schools in Massachusetts indicated that many shops had not measured noise levels, and hearing protection was required only about half as often as other safety equipment.¹⁶⁹ Interventions in this population have been shown to be effective¹⁷⁰; however, few high schools consistently include hearing conservation in their curricula.¹³⁸ A wide variety of hearing conservation materials designed for or adaptable to young workers is readily available, but there has not been widespread dissemination, implementation, or evaluation of these resources.¹³⁸ As many farm youths and industrial technology students will likely continue on these career paths in adulthood, hearing conservation efforts directed at them could have long-standing benefits in the reduction of occupational hearing loss.¹⁶⁸ Hearing loss prevention programs are especially important among farm youths because agricultural workers are not currently covered by any noise exposure standard.

An additional consideration for young, noise-exposed workers that has received little attention is the appropriateness of adult HPDs. Youths aged 16 and older can probably wear adult hearing protectors with similar benefit,

although this has not been empirically demonstrated. 3M and Aearo companies (now merged) have specific recommendations regarding hearing protection for children younger than 16 years^{171,172}; but again, the effectiveness of these recommendations has not been studied.

Older Workers

In 2008, there were over 6 million U.S. workers aged 65 and older.¹⁷³ In the 30 years between 1977 and 2007, employment of older workers more than doubled, and this trend is expected to continue. By 2016, workers aged 65 and older are expected to account for more than 6% of the total labor force.¹⁷³ Even without the deleterious effects of noise and other ototoxicants, older workers may have age-related high-frequency hearing loss. In some jobs, older workers' level of experience can compensate for their diminished sensory capacity, but this is not always the case.¹⁷⁴ Zwerling et al¹⁷⁵ reported that older workers with self-reported hearing loss had an increased risk of occupational injury. Recommendations for reducing injury risk for such workers include redundant warning signals (flashing lights, vibratory signals), reduced speech rate and elimination of compression on automated voice systems, and provision of telephone-amplifying devices.¹⁷⁴ Studies are needed to evaluate the effectiveness of these recommendations, as well as to identify other workplace accommodations that might reduce risk for older workers.

In addition, protecting older workers who may already have an age-related hearing impairment from additional hearing loss due to noise exposure is imperative. Workers with preexisting hearing loss may be disinclined to use conventional hearing protection because of communication interference (see section on hearing-impaired workers, p. 228). Methods of identifying workers with special hearing protection needs and selecting appropriate protective devices are especially needed for the older worker population.

Non-English-Speaking or Nonnative-English-Speaking Workers

According to the 2000 census, 18% of the U.S. population speaks a language at home other

than English, an increase from 14% in 1990 and 11% in 1980. More than 8% of U.S. residents have at least some trouble speaking English.¹⁷⁶ A disproportionate number of foreign-born individuals are employed in some noise-hazardous occupations, including operators, fabricators, and laborers.^{177,178} The language barrier and lack of acculturation can place these workers at greater risk for occupational injuries, including hearing loss. In addition, many non-English-speaking workers are employed in the "informal" work sector, where they may work long hours and be paid "off the books." In these situations, workers are unlikely to receive the benefits of formal occupational safety programs or feel empowered to insist on safe working conditions.¹⁶³

Focus groups among Latino construction workers found that new immigrants are the most likely to work without hearing protection, as safety equipment may not have been used in their home countries. In addition, the need for work and fear of losing their jobs discourage some foreign-born workers from asking for protective equipment.¹⁷⁹ Workers with limited English skills may not understand hearing loss prevention training materials or may find that HPDs further impede their ability to understand English speech. Rabinowitz and Duran¹⁸⁰ conducted hearing protector fit-testing in a population of industrial workers that included a large proportion of Hispanic immigrants. They found that the personal attenuation ratings were positively correlated with use of English. Furthermore, hearing thresholds were higher in workers with lower acculturation. Research is needed to identify factors that impede hearing conservation efforts among non-English-speaking workers and to develop programs that address these barriers.

An increasing number of hearing loss prevention materials are available in Spanish; however, there have been no studies of the efficacy of these materials. In addition, 380 languages are spoken in homes across the United States, including seven languages spoken by at least 1% of the population (Spanish, Chinese, French, German, Tagalog, Vietnamese, and Italian).¹⁷⁶ Although there appear to be few commercially available hearing conservation materials in languages other than English or Spanish in the

United States, the European Agency for Safety and Health at Work offers materials in some 23 languages (<http://osha.europa.eu/topics/noise/index.html>). To promote hearing conservation among non-English-speaking workers, it is necessary to either develop materials in additional languages or provide English-language training for these workers. Furthermore, it may be necessary to develop unique approaches to program delivery among foreign-born workers. For example, workers may fear government organizations but be open to training provided through churches or community centers.¹⁶³ Development and evaluation of hearing loss prevention programs targeted to the non-English-speaking population are needed.

Hearing-Impaired Workers

An estimated 19 million adults in the United States have some degree of hearing loss, and nearly half of these individuals are currently employed.¹⁸¹ An unknown number of these workers are exposed to high noise levels in their jobs; however, because many noise-exposed individuals develop high-frequency hearing loss in the first 5 to 10 years of employment,^{182,183} it can be surmised that a significant number of U.S. workers are both hearing-impaired and exposed to high levels of occupational noise. Although HPDs may improve speech intelligibility for normal-hearing workers in high noise occupational environments, workers with hearing loss may experience significant degradation of the speech signal under hearing protection.¹⁸⁴⁻¹⁸⁶ Inability of hearing-impaired workers to hear warning signals is another issue. Several studies have indicated that noise-exposed hearing-impaired workers may be at increased risk for occupational accidents,^{187,188} and focus groups conducted among these workers indicated that the workers perceive themselves at increased risk due to their hearing impairment.¹⁸⁹ However, hearing conservation regulations do not take into account the special difficulties encountered by hearing-impaired workers, and most hearing loss preventionists are unaware of how to address their needs.

Accommodation of noise-exposed hearing-impaired workers requires the development

of methods to protect workers' residual hearing without placing them at increased risk through overprotection, as well as tests to identify which method is most suitable for a particular worker and environment. Research should investigate ways that workers can be accommodated in the workplace, including the types of personal hearing protectors that are most beneficial to hearing-impaired workers, the types of aural amplification devices that would allow workers to perform work safely and efficiently, and other changes in the workplace that would lessen the emphasis on the acoustic signal. The research should consider the practicality and cost factors associated with the accommodation as well as workers' acceptance of the change in their environment.

OSHA has issued two Safety and Health Information Bulletins with recommendations for hearing conservation practices and safety accommodations for hearing-impaired workers.^{190,191} Recommendations include use of flat attenuation, level-dependent, or communication-equipped hearing protectors; possible use of hearing aids under earmuffs¹⁹²; implementation of appropriate alerting systems; provision of assistive devices such as Teletype or relay services, captioning, FM systems, and Web-based meeting software; and training of co-workers on assisting people with hearing impairments. These suggestions may fill a current information gap; however, all of the recommendations await evaluation as to their utility in practice.

Temporary and Mobile Workers

Temporary and mobile workers are those who change jobs or employers frequently (e.g., construction workers, migrant farm workers). These individuals pose a special challenge for hearing loss prevention. Because of the gradual development of hearing loss due to noise and the changing nature of employment for these workers, monitoring exposures and hearing sensitivity can be problematic. Many of their jobs are very fluid, indicating the need for a task-based exposure assessment system and methods of predicting exposures (and the need for hearing protection) in advance on the basis of existing data. Providing audiometric testing at the job site, rather than forcing

workers to travel to a remote testing site, would improve the effectiveness of hearing loss prevention. Noise measurement tools such as inexpensive dosimeters, which would inform workers of their exposures from task to task, would facilitate appropriate use of hearing protection. In addition, development of innovative record-keeping procedures, such as smart card technology or Web storage, would allow universal access to exposure and audiometric records.

A joint ANSI/ASSE consensus standard¹⁹³ concerning hearing loss prevention for construction and demolition workers (A10.46–2007) calls for audiometric testing and record keeping but includes provisions adapting the program to mobile workers. These provisions include the acceptability of audiograms performed by previous employers, a requirement to give employees a copy of their audiogram, and suggestions for a centralized record storage program. The success and viability of these programs in construction and similar industries need to be evaluated.

To accomplish these tasks, it is also necessary to clarify who is responsible for the health and safety programs for temporary or mobile workers (e.g., the contracting company or the contractor) and to develop incentives for hearing loss prevention in this workforce.

Workers Not Covered by Noise Regulations

Although most U.S. workers are protected by governmental regulations limiting workplace noise exposure, several occupational groups are not. Employees in oil and gas drilling, most agricultural workers, and certain federal and state government employees are not pro-

ected by noise regulations. The construction industry has a noise regulation and a mandate for use of HPDs when the noise exposure limit is exceeded, but no regulations covering other aspects of a hearing loss prevention program.¹⁹⁴ The impact of the lack of regulation on the hearing of workers in these industries needs to be documented, and information on methods of delivering appropriate hearing loss prevention tools to these industry sectors needs to be developed and disseminated.

RESEARCH NEEDS

- Investigate the impact of occupational noise and other ototoxins on the incidence of NIHLs in youths.
- Increase dissemination of hearing conservation materials among young workers, particularly through schools and agricultural programs.
- Evaluate the appropriateness of various hearing protection options and create demonstration programs in hearing conservation for children and hearing-impaired workers of all ages.
- Develop and test innovative ways to deliver hearing loss prevention training to non-English-speaking workers.
- Establish useful exposure monitoring, audiometric testing, and record-keeping methods for temporary or mobile workers and evaluate existing programs.
- Evaluate the impact of lack of noise regulation on the prevalence of occupational hearing loss among workers in industries not covered by such regulations, and develop hearing loss prevention programs tailored to these workplaces.

Record Keeping

Learning Outcomes: As a result of this activity, the participant will be able to discuss the key role that record keeping plays in successful hearing conservation programs and describe potential improvements that could increase their utility in preventing hearing loss.

Although it often receives less attention than other aspects of the program, documentation is actually one of the most critical components of a hearing loss prevention program. Results of noise monitoring, findings in audiometric testing, and other data collected in the course of hearing conservation do nothing to protect hearing unless they can be accessed and utilized. Complete and consistent record keeping over the long term is essential to success in hearing loss prevention.¹⁹⁵ Therefore, research leading to improvements in the ability to maintain and utilize program records is important.

One such improvement is the transition to electronic record storage. Many audiometers and sound measurement devices now offer data storage and transport capabilities that permit records to be transferred to databases very quickly. Electronic data systems offer many advantages, including the ability to flag incomplete documentation, identify unusual or questionable results, mark cases needing follow-up, prompt for necessary calibration of equipment, and cross-reference to other pertinent information. However, these advantages depend on well-designed database systems to coordinate information and provide meaningful reports.

Traditionally, hearing conservation programs have operated with disconnected data systems for health and exposure records. Investigations into the links required to integrate these two critical components are needed, and the best ways to accomplish this linkage should be identified. NIOSH developed a data management structure known as *HearSaf 2000* (<http://www.safe-at-work.com/HearSaf/overview.htm>), which stored sound exposure and hearing threshold data, as well as other information such as hearing protector usage and demographics, in a single database. (Unfortunately, the software is no longer available, and no company has stepped into the void to offer it.) Partnerships should be developed to market and implement usage of such a system and/or to

modify it as necessary to better meet the needs of hearing conservationists.

Integrated electronic record systems for hearing loss prevention programs have other advantages as well. Data accessibility is much improved, allowing hearing conservationists access to prior audiometric test results, noise exposure levels, hearing protection history, and so on, which allows better management of individual workers. Issues concerning accessibility rights need to be resolved to maximize data utility while preserving confidentiality. Electronic records also allow data retrieval to assist in program evaluation. Effective use of data permits program resources to be allocated more effectively and guides continuous quality improvement through statistical quality control. Research into the appropriate outcome measures to accomplish this is needed.

Electronic record systems can also assist in conducting surveillance activities. Consensus on a set of minimum data elements and standard variable definitions is necessary, as well as development of the necessary protections for confidentiality. Some work has already been accomplished, which could serve as a starting point. NIOSH has developed a standardized questionnaire for occupational health research¹⁹⁶ as well as a more detailed questionnaire specifically for noise and hearing (NIOSH 2000, unpublished). NIOSH is also developing a National Occupational Exposure Database, which incorporates recommendations by the Joint American Conference of Governmental Industrial Hygienists-American Industrial Hygiene Association (ACGIH-AIHA) Task Group on Occupational Exposure Databases.¹⁹⁷ Partnerships and consensus building are the missing components to utilizing existing hearing conservation program records as powerful tools for surveillance of noise and occupational hearing loss.

The potential utility of personal health records (PHRs) in hearing loss prevention is

another area that would benefit from investigation. The American Health Information Management Association and the American Medical Informatics Association advocate that individuals maintain a PHR to help manage their health care and to empower them in making health care-related decisions.¹⁹⁸ Applying the PHR concept to hearing conservation would allow workers to maintain hearing test records throughout their employment history and to disclose relevant information to a hearing conservation provider only as they deem it appropriate. In addition, promoting PHRs might increase the perceived importance of hearing conservation among workers, promote understanding, improve their sense of control over their hearing, and increase protective behaviors. Studies investigating the utility of PHRs in hearing loss prevention, their acceptability among worker populations, and various record formats and PHR technologies are warranted. Resources on the general concept of PHRs (e.g., www.myphr.com) are available and could serve as a starting point in this process.

Finally, training programs for hearing conservationists and managers regarding the critical importance of good record-keeping procedures are needed. In a survey of hearing conservation programs in Washington State, Daniell et al¹⁹⁹ found that most companies conducted noise

monitoring but few maintained records of such. OSHA regulations require retaining noise monitoring records for only a limited time, but the utility of this information far exceeds the regulatory requirement. Impressing management with the significance of hearing conservation records and the potential consequences of not maintaining complete, consistent documentation of every aspect of a hearing loss prevention program would be a significant step toward reducing NIHL.

RESEARCH NEEDS

- Develop improved systems to integrate, manage, and access hearing loss prevention program records.
- Design outcome measures to utilize hearing loss prevention records for program evaluation.
- Investigate possibilities for compiling records of hearing loss prevention programs into a central repository that could be used for surveillance purposes.
- Explore the feasibility and utility of applying PHRs to hearing loss prevention.
- Develop and evaluate methods to encourage management to understand the importance of a well-maintained record-keeping system.

Program Evaluation

Learning Outcomes: As a result of this activity, the participant will be able to discuss the importance of program evaluation as an essential component of successful hearing loss prevention programs and identify available evaluation metrics.

Evaluation of the performance of HLPPs is an essential component of protecting workers from NIHL. In an investigation of noise exposure and hearing loss after 20 years of regulation in the United States, Daniell et al¹⁹⁹ found that most programs had serious shortcomings that could impact the effectiveness of their hearing loss prevention efforts. Clearly, suitable evaluation techniques are necessary to promptly identify and correct program weaknesses so that workers' hearing is protected. However, there is no regulatory guidance on how to conduct this type of evaluation.²⁰⁰ In its 1998 revised criteria document,³⁹ NIOSH reviewed several program evaluation methods and concluded that no single method was best.

The most basic evaluation method is the use of a checklist to verify program compliance with regulatory requirements and company policy. Several checklists are available that can be adapted to the needs of a particular program (see, for example, NIOSH⁷¹ and Royster and Royster¹²⁷). However, checklists evaluate only program compliance and not program effectiveness.^{199,200} Wolgemuth and colleagues²⁰⁰ found only a weak relationship between compliant hearing conservation programs and the incidence of threshold shifts.

Because the goal of an HLPP is the prevention of hearing loss, one obvious measure of program effectiveness is the rate of threshold shift among noise-exposed employees. On the basis of non-noise-exposed population data from ANSI S3.44-1996, *Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment*, NIOSH³⁹ recommended an annual STS rate no greater than 3% as an indicator of program success. An advantage of this approach is that it makes use of information already calculated for OSHA compliance purposes. Examination of other factors in conjunction with STS rates has been shown to identify program weaknesses. Rabinowitz and colleagues²⁰¹ noted that STS rates were highest among employees with exposures less than or equal to 85 dBA, suggesting

perhaps that lack of hearing protector use by these workers was allowing hearing shifts to occur. But there are disadvantages to the STS approach as well. Using STS rates could require accumulating data over several years, allowing hearing losses to develop before problems are noticed. Simpson et al²⁰² noted, however, that successful versus unsuccessful programs could be distinguished with audiometric data spanning just a 2-year period, although presumably a relatively large number of employees would be necessary to accomplish this. Also, prevalence of STS tends to increase with increasing age, unless age adjustments are incorporated.²⁰³ The STS evaluation procedure does not account for other relevant factors, either, including gender, race, prior exposure history, and nonoccupational issues.^{39,204}

Variations on the STS method include average change in hearing levels over time²⁰³ or comparison of hearing change over time in groups exposed to various levels of noise.²⁰⁵ These methods require more computation, but the increasing use of electronic records could allow a wide variety of descriptive statistics on processes and outcomes to be readily produced to measure program participation, quality assurance, and program effectiveness. Developing and testing new evaluation metrics based on data already collected as part of the hearing conservation program would be an important contribution to hearing loss prevention.

In an effort to avoid the latency inherent in some STS approaches, audiometric database analysis (ADBA) was proposed as an evaluation technique. ADBA utilizes year-to-year variability in audiometric thresholds as a measure of program performance, under the assumption that excessive threshold fluctuation indicates TTS resulting from inadequate hearing protection. An advantage to this procedure is that it could identify relatively small shifts in hearing before more significant threshold shifts occur. An analysis of ADBA metrics compared with STS rates in audiometric data sets from 22 hearing conservation programs showed that

ADBA results were highly correlated with STS rates.²⁰⁶ Problems with ADBA include the dependence of ADBA metrics on the 5-dB step size used in audiometric testing²⁰⁷; the correlation of ADBA statistics with baseline hearing levels²⁰⁸; the exclusion of workers who do not have long audiometric monitoring histories^{209–211}; and the large number of audiograms or large size of the population needed. Nonetheless, ADBA has been formalized in an ANSI technical report (ANSI S12.13 TR 2002)²¹² and can be a valuable tool in program evaluation.

Epidemiological principles can also be applied to program evaluation. Relative risk is the ratio of the probability of a disease (e.g., hearing loss) in an exposed versus unexposed population. The rate of hearing loss among workers enrolled in a hearing conservation program can be compared with the rate of hearing loss in a reference population, and the results can be tested statistically. If the rates are similar, then the hearing loss prevention program is judged to be successful. Adera et al^{209,210,213} described procedures for conducting these comparisons. The key to this approach, however, is finding an appropriate reference population. In theory, the populations should be completely similar except for occupational noise exposure; and to the extent that this is not true, the measure loses validity. Some generic reference databases are available as comparison populations,^{214,215} or reference data can be drawn from non-noise-exposed employees at the same company (if that group is demographically similar to the noise-exposed group). Identification of other reference populations is warranted. An advantage of the epidemiological approach is that confounding variables—age, gender, race, nonoccupational exposure, and the like—can be considered, if such data are available. However, as with the STS rate, epidemiological methods such as these identify problems with hearing conservation programs only after hearing loss has occurred. Moreover, their effectiveness is generally limited to companies with a sufficiently large noise-exposed workforce. Development of other key indicators that could be incorporated into an epidemiological model and the possible application of other epidemiological techniques (such as surveillance) would be useful areas for further research.

Other aspects of program evaluation have scarcely been investigated at all. For example, one criterion could simply be the number of employees exposed to levels at or above 85 dBA, 90 dBA, or other higher levels on a yearly basis, with the goal of reducing these numbers as noise control measures are implemented. Prince et al²¹⁶ proposed that qualitative information be gathered from employees to gain a more complete picture of the effectiveness of hearing conservation programs and to provide insights on deficiencies and workable means of remediation. Stephenson and Stephenson¹¹⁸ have developed a survey that has been demonstrated to measure how well training influences attitudes, beliefs, and behavioral intentions regarding hearing protector use.¹¹⁹ NIOSH is currently studying the use of hearing protector fit-testing. It appears that fit-testing may hold much promise for determining how well training has taught workers to properly fit their ear plugs. Work by Simpson and colleagues²¹⁷ suggests that methods are needed that are appropriate for small businesses having only small databases of hearing records and limited resources for evaluation. They found that ADBA was difficult in companies with fewer than 100 employees, and checklists overestimated program effectiveness.

A recent Cochrane collaboration examined the effectiveness of HLPPs as a whole rather than only HPDs. Twenty-one studies met the reviewers' criteria for inclusion in the review, several of which showed some benefits from these programs, although there was often a risk of bias. The reviewers determined that the overall quality of these studies was low.²¹⁸ With all the time, effort, and resources being devoted to HLPPs, as well as the serious impact of failure, careful evaluation of program interventions should be a high research priority.

Evaluation of the economic impact of a hearing loss prevention program should not be overlooked. Necessity dictates that companies pay attention to their cost of operation. However, little work has been done to establish the economic benefits of early identification of NIHL, which could present to management a powerful argument in favor of hearing loss prevention activities. Bertsche et al²¹⁹ published a method for determining the

cost-effectiveness of audiometric monitoring; additional research to establish mechanisms for evaluating the economic benefit of other aspects of hearing conservation would be useful. "Economic Impact of Occupational Hearing Loss" in Part 1 (pgs. 176–181), on measuring the overall economic consequences of noise exposure and hearing loss, contains further information on this topic.

Probably a single evaluation method will not be sufficient to adequately assess a given hearing loss prevention program. Researchers must determine which combination of methods provides the best overall assessment. Recommendations should be developed for companies of various sizes and resources to make certain that program evaluation is manageable for all hearing loss prevention programs.

RESEARCH NEEDS

- Develop and test new evaluation metrics that can be calculated from data already

collected as part of the hearing conservation program.

- Further evaluate the various HLPP interventions to assess their relative effectiveness.
- Identify key indicators other than hearing loss rates that could serve as measures of program performance.
- Investigate the utility of other epidemiological methods for program evaluation.
- Develop program evaluation techniques that address worker perceptions, economic impact, and other overlooked aspects of hearing loss prevention.
- Identify combinations of evaluation methods that provide comprehensive program assessment for all businesses, regardless of variabilities in size and resources.
- Develop other leading indicators of HLPP effectiveness, such as number and percent of workers at risk.

Treatment and Rehabilitation

Learning Outcomes: As a result of this activity, the participant will be able to identify the unique aural rehabilitation needs of workers whose hearing has been damaged by noise and describe the strengths and limitations of new pharmaceutical approaches to preventing or reversing noise damage.

Despite more than three decades of regulated hearing conservation efforts in the United States, many workers have sustained and continue to develop occupational hearing loss. Hearing conservationists focus their primary effort on prevention of additional hearing losses. Although this is laudable, another area has been almost wholly overlooked. Workers who have already suffered occupational hearing loss often require aural rehabilitation. Systems are in place to provide injured workers with, at best, some monetary compensation and perhaps a hearing aid. However, the rehabilitative needs of hearing-impaired workers go far beyond this.²²⁰

Traditional aural rehabilitation programs may not be sufficient to meet the unique needs of workers whose hearing loss is due primarily to noise. Such programs generally focus on hearing aid use and speech reading skills, which may not suffice to deal with the ongoing stress of working in a noisy environment and adjusting to a sensory loss that may not be amenable to hearing aids. In addition, aural rehabilitation programs may only be offered through hearing centers or medical offices in locations that are remote from the worker's residence or workplace and at times that may not suit a full-time work schedule. Furthermore, the rehabilitation community has made little outreach to the occupational community to inform them of the potential benefits of participating in such programs.²²¹ Development of new approaches to bring rehabilitation to persons with occupational hearing loss would be beneficial. Lalande and colleagues²²¹ suggest conducting sessions at work sites, integrating rehabilitation programs into the company's overall health and safety system, and raising overall awareness of problems associated with NIHL. These approaches and others need to be tested in and disseminated to the occupational health community.

Specific guidelines for occupational aural rehabilitation programs were initially published

in the United States in 1979.^{222,223} Subsequently, researchers in other countries developed and tested various rehabilitation programs for occupationally hearing-impaired workers.^{220,221,224,225} Results were generally positive. Lalande and colleagues²²¹ reported a better understanding of the disabilities associated with NIHL among program participants and new and more consistent use of communication strategies. Getty and Héту²²⁴ found that participants reported better awareness of their hearing problem and increased confidence in dealing with it. Hallberg and Barrenäs²²⁵ found a short-term reduction in perceived handicap among program participants, although this reduction was not evident 4 months following the program. Although the programs were largely successful, the participation rate among workers with NIHL was very low. Lalande and colleagues²²¹ reported only an 11% participation rate, and fewer than 50% of eligible workers participated in the program by Hallberg and Barrenäs.²²⁵ Getty and Héту²²⁴ obtained an 89% participation rate by recruiting through occupational health nurses who were already familiar to the workers.

Results from these programs point to specific suggestions for further research. Topics identified for inclusion in aural rehabilitation programs for NIHL (as described in Lalande et al,²²⁰ Getty and Héту,²²⁴ and Hallberg and Barrenäs^{225,226}) need to be revisited in view of changing workplace and communication technologies. Although all three programs used a group approach and included a spouse or other family member, Lalande et al²²¹ suggest evaluating other formats such as individual sessions and targeting specific problems. Furthermore, Westbrook et al²²⁷ suggested that different approaches to rehabilitation based on personal coping strategies are needed. Hallberg and Barrenäs²²⁵ proposed following the group rehabilitation program with additional sessions or the formation of self-help groups to maintain the effects noted in the short term but lost over the

long term. In view of the recruitment problems, Getty and Héту²²⁴ recommend training other professionals with whom the workers may be more comfortable to conduct the aural rehabilitation program. They developed a training guide (available in French²²⁸), but its efficacy has not been broadly tested. Workers who have already sustained NIHL could benefit from research into these aspects of rehabilitation programs. In addition, Getty and Héту²²⁴ suggest that proliferation of rehabilitation programs for NIHL would raise awareness of occupational hearing loss in general, ultimately encouraging reduction of workplace noise.

Although aural rehabilitation for occupational hearing loss has received scant attention, a great deal of time and press is being devoted to pharmacological treatment possibilities for NIHL. The discovery that metabolic processes in the cochlea are at least partly responsible for noise-induced damage has led to a surge in research to identify and test possible pharmacological therapies.²²⁹ Scientists are investigating a range of compounds ranging from vitamin supplements to new pharmaceuticals that might intervene in the destructive cochlear processes initiated by noise and other ototoxic agents.^{229–234} Interventions are oriented toward prevention of the generation of reactive oxygen species (ROS) and free radicals in cochlear cells (e.g., antioxidant therapies such as vitamins A and C), preventing the initiation of apoptosis (e.g., through caspase inhibitors such as *N*-acetylcysteine), and upregulating survival factors (e.g., growth hormones and neurotrophins) to shift the balance between cell death and cell survival.^{229,231,235}

Although therapeutic interventions such as these are exciting and potentially promising, they are not a panacea. Studies to date show mixed results, due at least in part to the use of different animal species and dosing regimens across investigations. Other factors may also limit the utility of pharmacological therapies for NIHL. The half-life of a compound and problems delivering it to affected cells may limit its efficacy. Not all compounds may be suitable for all free radicals. The molecular cascade that leads to cell death is still not completely understood; there may be important metabolic pathways that are not associated with ROS but still lead to cochlear injury. Because ROS and

endogenous antioxidants are normal facets of cellular function, it is important to achieve the correct balance between inhibiting cochlear damage and maintaining normal cell activity. Mechanical damage to cochlear structures remains a component of NIHL that is not amenable to correction by pharmaceutical means.²³⁰ Finally, these approaches to the prevention of NIHL have been limited to PTSs, showing little or no effect on the TTSs produced by the exposure.²³³

In addition, most experiments have involved dosing prior to exposure.²³⁵ In the real world, if the noise exposure is anticipated, there are surer means of prevention through the hierarchy of controls (noise reduction, personal protection). If the exposure is unanticipated, pharmacological interventions after the fact may help reverse the deleterious effect of the noise, but few studies to date have investigated the critical time window in which these agents are effective.²³⁵ Although basic science in this area is important and should continue, it should not detract from current efforts to reduce exposures, improve protection, and provide rehabilitation to persons already suffering from NIHL.

One additional recent development deserves mention. Damage to cochlear cells from age, noise, and ototoxic insults has always appeared permanent. The sensory cells of the ear are fully formed early in development and are called “quiescent,” meaning that further cell division and replacement do not occur. This was assumed to be the case across species. However, recent studies in birds have found that the basilar papilla (the avian equivalent of the organ of Corti) is quiescent only as long as it remains undamaged. When avian inner ear cells are damaged, the supporting cells are stimulated to divide; the resulting cells can be differentiated into either additional supporting cells or replacement sensory cells. Until recently, this type of regeneration had not been demonstrated in any mammalian species. But there is now evidence that limited regeneration can occur in mammalian species. Experiments by Zheng et al²³⁶ elucidated self-repair processes in rat stereocilia, and Izumikawa et al²³⁷ noted regenerated hair cells and improved hearing thresholds in guinea pigs after genetic treatments. Scientists hope that further research will identify the mechanisms that control the

quiescence of cells in the body, perhaps opening up the possibility of replacing damaged cochlear cells in humans.^{238,239} Such research and its applications are outside the scope of the research recommendations of this document; however, their potential importance in eventually treating existing NIHL cannot be overlooked.

RESEARCH NEEDS

- Determine the magnitude of workers needing aural rehabilitation because of NIHL.
- Develop and test relevant aural rehabilitation programs for workers who have sustained occupational hearing loss.
- Identify mechanisms for improving workers' accessibility to aural rehabilitation.
- Evaluate the possibility of training other professionals to provide aural rehabilitation programs for hearing-impaired workers.

Public Health Perspective

Learning Outcomes: As a result of this activity, the participant will be able to identify hearing loss prevention in the larger context of public health and the relationship between preventing noise-induced hearing loss from off-the-job as well as on-the-job exposures.

Prevention of occupational hearing loss is a significant part of a still larger picture: prevention of all hearing loss due to noise or other ototoxic exposures. Protecting workers on the job is important, but it is also crucial to raise awareness and encourage protective behavior when individuals are exposed to noise outside of work. Furthermore, raising awareness of NIHL in the general public would facilitate prevention of NIHL at work.

Despite over 30 years of noise regulation across most industries in the United States and abroad, NIHL remains one of the most prevalent occupational conditions.²⁴⁰ Furthermore, recent studies have begun to highlight evidence of early NIHLs in children.^{105,241} Present efforts are evidently insufficient to prevent hearing loss from noise. In addition to education and motivational programs in the workplace, public health campaigns directed toward the general population are indicated. Efforts to elicit concern about workplace noise exposures above 85 dBA may be undermined by the social acceptability of noise in the general environment. When sports announcers gleefully encourage audiences to raise stadium noise levels well above 100 dB and commercials urge consumers to install powerful speaker systems in cars, it is evident that there are issues beyond the workplace.

Some public health interventions for NIHL have been tested. Weichbold and Zorowka^{242,243} initiated hearing protection campaigns to encourage adolescents to engage in hearing protective behavior at discotheques or alter their music listening habits. Neither campaign was successful. Randolph et al²⁴⁴ evaluated the relative effectiveness of lecture versus print materials for educating school-aged children about noise and hearing loss; they reported that the lecture intervention was more effective. Karlsmose et al²⁴⁵ found that adults who participated in a hearing screening and were counseled about noise exposure were more likely to

report avoiding leisure noise 5 years later than adults who did not have their hearing screened. However, a poster campaign initiated by King et al²⁴⁶ to encourage adults to have their hearing tested went largely unnoticed by the target population. These efforts are a very small step in the journey toward raising public awareness of noise and hearing loss.

Several professional organizations have designed educational tools and public service announcements to inform various segments of the population about NIHL. Media campaigns have included "Wise Ears" by the National Institute on Deafness and Other Communication Disorders (<http://www.nidcd.nih.gov/health/wise>), "Listen to Your Buds" by the American Speech-Language-Hearing Association (ASHA; <http://www.listentoyourbuds.org>), and "Earbud" by the House Ear Institute (<http://www.earbud.org>). ASHA reported donated media resources of nearly \$2.3 million in over 7000 television ads, 33,000 radio spots, and 350 print public service announcements for a campaign featuring James Earl Jones in 2000 to 2001.²⁴⁷ However, no measure of the impact of this or any other public health audiology campaign is available in the literature. Evaluating the effectiveness of campaigns such as these is important to ensure that resources are targeted toward efforts and audiences for which the impact will be greatest.

Health promotion is a science unto itself. As with worker training programs, merely supplying information is seldom enough to change behavior. Social marketing, which involves integration of marketing principles with social-psychological theories of human behavior, has been more successful in producing the desired action. Media advocacy, which utilizes the mass media more to pressure policymakers than to influence individuals, has also been successful.²⁴⁸ Research on the applicability of approaches such as these to hearing loss prevention is needed, however. Hearing

conservationists must partner with health promotion experts to design effective campaigns that will influence people to protect their hearing.

Various subpopulations should be especially targeted for public health interventions. School-based programs are important to teaching children healthy hearing behaviors before destructive habits are formed.²⁴⁹ Incorporating noise training into engineering programs could increase awareness of noise reduction at the design level, encouraging quieter industrial and recreational equipment. Similarly, expanding the training of other health professionals to understand the hazards of noise and recognize signs of hearing loss could increase opportunities for patient education and lead to earlier diagnosis of and intervention for noise-induced hearing problems. In all these cases, partnerships with other professionals are necessary to reach the target population and ensure successful programs. In addition, development of effective measures to assess and track the impact of public health interventions is crucial.

Public health campaigns have been successful in reducing other risk behaviors. Smoking rates among U.S. adults declined by 0.5 to 1.1% each year from 1965 to 1990 on account of massive efforts to educate the public about the hazards of smoking, to provide environments conducive to changing smoking habits, and to decrease the social acceptability of smoking behaviors.²⁵⁰ Increasing the awareness of noise as a public health problem should be a priority among those concerned with occupational hearing loss.

RESEARCH NEEDS

- Develop and implement measures to evaluate the impact of noise-related public health interventions.
- Partner with health educators, public relations professionals, and others to develop effective public health campaigns focused on noise and hearing.
- Encourage training regarding NIHL in targeted educational arenas, including grade schools and high schools, engineering programs, and courses for health professionals.

Implementation

Learning Outcomes: As a result of this activity, the participant will be able to describe barriers that have hindered implementation of hearing loss prevention strategies in the past and identify the importance of collaboration to ensure better implementation in the future.

Too often research results are published in technical and scientific journals, accessed by a few interested professionals, and then relegated to the file cabinet. This can be the case especially with pragmatic disciplines such as occupational hearing conservation, whose practitioners may gather for professional meetings only once a year, if that. One of the Institute of Medicine's important recommendations to NIOSH in its recent report on hearing loss research²⁶ was outreach to and input from the communities responsible for preventing occupational hearing loss. This would include the areas of noise control engineering, low-noise product design, epidemiology, and management of hearing conservation programs. The report recommends collaborations with other agencies, academic scientists, employers, and workers. For example, the report acknowledges the work of NIOSH on engineering controls for mining but notes that this work has had little impact on industrial sectors beyond mining. Certainly, there must be a multitude of practical, cost-effective noise control solutions that are not being applied because few people know about them. Furthermore, more attention must be given to perceived barriers to the implementation of noise controls. Health communication strategies shown to be effective in improving workers' attitudes and beliefs about hearing protector use¹¹⁹ should be studied to assess their application regarding noise controls. Another reason why such control programs are not being implemented is that they are not currently required by OSHA. By contrast, the experience of MSHA indicates that the presence and enforcement of regulation do appear to decrease the median noise dose for the affected workers.²⁵¹ This is consistent with data presented in a recent Cochrane Review²¹⁸ that described a positive relationship between noise legislation and decreased noise exposure levels.

Another reason for concern about proper implementation of research is the importance of workers' beliefs and attitudes and the disconnect that can occur between the purveyors of hearing loss prevention programs and the workers themselves. Although hearing conservation professionals strive to increase workers' acceptance and use of HPDs, the workers themselves often have negative attitudes based on their own experience. Take, for example, the findings of Svensson et al²⁵² from interviews with noise-exposed Swedish workers:

- 95% were aware that loud noise could lead to hearing damage
- 90% considered hearing loss a serious problem
- 85% believed that HPDs could protect their hearing
- 55% believed that they could not hear warning signals when wearing HPDs
- 45% considered HPDs to be uncomfortable

Research discussed in the "Program Evaluation" section (pgs. 232–234) concerning the evaluation of HLPPs showed many of the shortcomings of these programs. Most of the studies cited by the Cochrane Review were, according to the reviewers, of low quality.²¹⁸ Because the nation in general and employers in particular devote so many resources to protecting workers against the harmful effects of noise, all of these implementation strategies need to be carefully evaluated. An even more compelling reason to do so is to identify the most effective (and discontinue the ineffective) means of preventing the disabling loss of hearing that is still epidemic today.

This document summarizes the current state of knowledge and highlights research needs on noise-induced hearing impairment and other adverse effects of occupational noise. In addition to hearing loss, several other effects of noise are discussed, such as the effects of

noise on tinnitus, workplace safety, and extra-auditory health, as well as the effects of noise, hearing impairment, and HPDs on communication and perception of warning signals. The document also includes research findings on strategies to combat these adverse effects by increasing the effectiveness of hearing loss prevention programs through noise control, HPDs, training and education, program evaluation, and other interventions and critical program components. The intent of the research recommendations in each of the 25 topic areas presented in this publication is to provide broad recommendations regarding the need for additional knowledge to prevent occupational hearing loss. Although this publication does not prioritize or limit any of these recommendations, NIOSH has adopted a strategic plan that does include prioritized research goals for preventing occupational hearing loss. More information about these prioritized research goals can be found on the NIOSH Web site, at www.cdc.gov/niosh/programs/hlp/goals.html.

Research needs are not limited to those discussed here, but many of these identified needs are of utmost importance to the health and safety of American workers. NIHL is permanent, and its effects are experienced not only by individuals but also by families and society as a whole. Because good hearing is not restorable through hearing aids, prevention of hearing impairment is paramount. Research findings that clarify the extent and effect of noise hazards and elucidate the most effective means of reducing these hazards are of interest to individual workers as well as the general population. For too long the results of many important investigations, private as well as public, have been overlooked and underutilized. Therefore, the effective application of current and future research findings is essential.

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DEDICATION

To Dr. Daniel L. Johnson, whose wisdom and humor will always be missed.

NOTES

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National Research Agenda for the Prevention of Occupational Hearing Loss; Guest Editor, Mark R. Stephenson, Ph.D.

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Self-Assessment Questions

This section provides a review. Mark each statement on the Answer Sheet according to the factual materials contained in this issue and the opinions of the authors.

Article One (pp. 147–149) Prevalence of Noise Exposure in the Workplace

1. The Occupational Safety and Health Administration (OSHA) studied the manufacturing sector during its preparations to develop the current hearing conservation standard (29 CFR 1929). When it did so, what percentage of the manufacturing sector workers were exposed to daily time-weighted average noise levels of 80 dBA or above?

A. 70%
B. 60%
C. 50%
D. 40%

2. In their 1998 study of noise exposure and hearing loss among construction workers, Neitzel and his colleagues determined that using a 3-dB exchange rate instead of a 5-dB exchange rate would

A. increase the number of workers exposed to hazardous noise
B. decrease the number of workers exposed to hazardous noise
C. have no significant effect on the number of workers exposed to hazardous noise
D. yield invalid noise measurement results

3. A recent study by the National Institute for Occupational Safety and Health (NIOSH) shows that the number of overexposed workers may be higher than the original estimate of 9 million. According to Tak and his colleagues, the number may be closer to

A. 12 million
B. 22 million

C. 32 million
D. 42 million

4. True or false? Because noise survey methodologies have relied on instruments calibrated to *American National Standards Institute* (ANSI) standards, it has not been difficult to compare older studies with modern studies.

Article Two (pp. 150–154) Risk Assessment

5. Policy considerations that affect the development of hearing damage risk criteria include

A. whether to use ANSI standards or Environmental Protection Agency (EPA) guidelines for sampling noise exposures
B. what proportion of the noise-exposed population should be protected
C. the amount of hearing loss that constitutes an acceptable risk
D. all of the above
E. B and C only

6. OSHA defines hearing impairment as
 - A. an average hearing loss of 25 dB at 500 Hz, 1000 Hz, and 2000 Hz
 - B. an average hearing loss of 25 dB at 1000 Hz, 2000 Hz, and 3000 Hz
 - C. an average hearing loss of 25 dB at 1000 Hz, 2000 Hz, 3000 Hz, and 4000 Hz
 - D. an average hearing loss in either ear of 10 dB at 2000 Hz, 3000 Hz, and 4000 Hz

7. If there is to be no risk of any hearing loss from noise exposure, even among the most sensitive members of the exposed population, then the permissible 8-hour average exposure limit would have to be as low as
- A. 75 dBA
 - B. 80 dBA
 - C. 85 dBA
 - D. 90 dBA
8. The risk of developing an occupational hearing loss is based on
- A. age, gender, and ethnicity
 - B. exposure levels and duration
 - C. policies that enforce the use of hearing protectors for workers exposed to high (>95 dBA) noise levels
 - D. all of the above
 - E. A and B only

Article Three (pp. 155–160) Impulse/Impact Noise

9. Impulse and impact noises are both short-duration transient acoustic events. However, impact noise differs from impulse noise in that
- A. impact noises are longer in duration and may also have a different character such as “ringing” after the impact
 - B. impact noises are swifter, shorter events than impulse events
 - C. impact noises have higher peak sound pressure levels than impulse noises
 - D. impact noises refer to occupational events while impulse noises refer to recreational events
 - E. both B and C
10. Impact and impulse noises are collectively referred to as
- A. intermittent hazardous noise
 - B. short-duration overpressures
 - C. impulsive noise
 - D. all of the above, depending upon the context

11. The A-duration of an impulse sound is defined as
- A. the duration over which time-weighted average dosimetry integrates impulsive events
 - B. the interval between two peak impulses when using A-weighting
 - C. the rise time of an impulse from onset to maximum peak sound pressure level
 - D. the time from ambient sound pressure level to the peak and return to ambient level
12. Recent research has demonstrated that the ideal metric for evaluating the hazard posed by exposure to impulse sounds is
- A. the OSHA permissible exposure limit of 140-dB peak sound pressure level (SPL)
 - B. measurements of the kurtosis of the peak SPL
 - C. the measurement of equal energy when the L_{eq} exceeds 90 dBA
 - D. none of the above

Article Four (pp. 161–164) Surveillance

13. Which of the following statements is true?
- A. In 2006, NIOSH established an ongoing national surveillance program for noise exposure.
 - B. With the promulgation of the OSHA Hearing Conservation Amendment in 1983, the U.S. Department of Labor was able to establish the first national database of occupational hearing loss.
 - C. Since the passage of the Walsh-Healy act in 1968, employers have been required to track cases of employee hearing loss.
 - D. There is no ongoing national hearing loss surveillance program.
14. Employers are discouraged from voluntarily reporting noise exposure data and audiometric data because
- A. of the difficulty to rely on field calibration of noise dosimeters

- B. of the potential for litigation and regulatory action
- C. of *Health Insurance Portability and Accountability Act* (HIPAA) regulations that make it difficult to share audiometric data
- D. both A and B
15. The Bureau of Labor Statistics database of occupational illness and injury
- A. did not track occupational hearing loss before 2004
- B. records hearing changes that meet the Standard Threshold Shift Criteria (an average shift of 10 dB in either ear at 2000, 3000, or 4000 Hz)
- C. requires age correction to be made when determining if an occupational hearing loss is recordable
- D. all of the above
16. The OSHA Integrated Management Information System
- A. is a database that contains the information on occupational injuries (including hearing loss) that have been recorded on the OSHA Log 300
- B. is a database that integrates hearing loss data collected from individual state-based data systems
- C. is a new database that contains hearing loss and noise exposure records by state and industry
- D. contains noise exposure measurements collected during compliance or consultation visits
- Article Five** (pp. 165–167) Mechanisms of NIHL
17. The continued cell death that can occur within the cochlea for several weeks following severe noise exposure is the result of
- A. metabolic stress that increases reactive oxygen species within cells thereby triggering apoptotic cell death
- B. necrotic cell death along the basilar membrane
- C. retrograde fusion of stereocilia to the tectorial membrane
- D. progressive embolytic reactions within the stria vascularis
- E. all of the above
18. Pathophysiologic changes from excessive noise exposure include
- A. repetitive stress trauma to the incu-stapedial joint
- B. stereocilia becoming fused, broken, or dislodged from the tectorial membrane
- C. disruption of the potassium cycling pathway through the outer hair cells, endolymph, and stria vascularis
- D. both A and B
- E. both B and C
19. Disruption of cochlear blood flow has also been previously implicated in the development of noise-induced hearing loss (NIHL). This includes
- A. vasoconstriction of microvascularization within the tectorial membrane causing it to stiffen and become separated from stereocilia tips
- B. aneurisms within the vascular supply to the scala media that disrupt the dendritic polarization of both inner and outer hair cells
- C. swelling within the stria vascularis, causing the death of intermediate cells and permanently shrinking the stria vascularis
- D. all of the above
20. Studies of the relationship between temporary threshold shift and permanent threshold shift have demonstrated that
- A. temporary threshold shift (TTS) magnitude is well correlated with susceptibility to permanent threshold shift (PTS)
- B. the underlying mechanisms for TTS are similar to those for PTS
- C. the uncoupling of the stereocilia from the tectorial membrane and the resulting change in hearing sensitivity are thought to be a principal factor in the correlation between TTS and PTS
- D. all of the above
- E. none of the above

Article Six (pp. 168–170) Factors Influencing Susceptibility

21. Individual susceptibility to noise-induced permanent threshold shifts
- A. is greatest after many years of exposure
 - B. is greater during the early years of exposure and then individual differences lessen
 - C. is greatest for noise exposures that exceed time-weighted averages (TWAs) of 100 dBA
 - D. both B and C
 - E. none of the above
22. Although some research has shown associations between certain extrinsic, physiological, or molecular factors and susceptibility to NIHL
- A. it is clear that there is no valid, reliable indicator of susceptibility
 - B. these associations warrant continued study to develop a test for susceptibility
 - C. only additional surveillance on those having been identified with noise-induced permanent threshold shift (NIPTS) is likely to prove fruitful
 - D. all of the above
 - E. both A and B
23. Lifestyle choices such as diet and exercise
- A. have been ruled out as factors related to individual susceptibility to NIPTS
 - B. may be associated with NIPTS and should be studied further
 - C. have been proven to be a factor in individual susceptibility to NIPTS
 - D. are interrelated to so many additional factors, such as nutrition, age, and gender, that other research should first be completed before conducting additional research on lifestyle factors
24. Research on genetic factors that may be related to susceptibility to NIPTS includes
- A. genes associated with the cochlear antioxidant system

- B. genes associated with fragile-X syndrome
- C. genes associated with nonoblitus vascularis
- D. all of the above

Article Seven (pp. 171–173) Ototoxicity and Combined Effects

25. Industrial agents that are considered to be ototoxic include
- A. styrene, neoprene, diacetylene
 - B. mercury, citrine, styrene
 - C. benzene, miocene, xylene
 - D. mercury, toluene, styrene
 - E. both C and D
26. Ototoxicants
- A. are most likely to damage outer hair cells when they are absorbed through the round window
 - B. are much more likely to cause damage to the stria vascularis than the cellular structures that support the organ of Corti
 - C. may damage hearing even without the addition of hazardous noise
 - D. both B and C
27. Dose–response relationships for ototoxicants
- A. have recently been published in the NIOSH Recommended Exposure Limits for ototoxicants
 - B. are contained in Appendix H of the OSHA Standard, 29 CFR 1929, Exposure to Physical Agents
 - C. have been published as threshold limit values (TLVs) for physical agents by the American Conference of Governmental Industrial Hygienists (ACGIH)
 - D. are not available
28. Because exposures to chemicals used in occupational environments
- A. can affect several areas of the central nervous system, relying on pure-tone behavioral audiometry alone may not provide a sufficient indicator of damage
 - B. causes initial damage to the cochlea, early detection is best accomplished by pure-tone audiometry

- C. have their greatest effect in the apical regions of the cochlea, high-frequency audiometry is especially useful in identifying effects
- D. none of the above

Article Eight (pp. 174–175) Consequences of Occupational Hearing Loss

29. The negative impact of noise-induced hearing loss includes
- A. loss of intimacy
 - B. both safety and communication at work
 - C. reduced ability to relate to sounds in one’s environment
 - D. all of the above
 - E. both B and C
30. The negative consequences of NIHL
- A. are directly proportional to the amount of hearing loss
 - B. lessen over time as workers adapt to the hearing loss
 - C. are only somewhat dependent upon the degree of handicap
 - D. both A and B

31. Conventional hearing conservation programs
- A. do not distinguish between workers with normal versus workers with impaired hearing
 - B. are required by OSHA to adjust workers’ tasks to reflect potential inability to hear warning sounds
 - C. include specific training for workers with noise-induced hearing loss on how to select hearing protectors that will help them communicate while on the job
 - D. both B and C

Article Nine (pp. 176–181) Economic Impact of Occupational Hearing Loss

32. Noise exposure and occupational hearing loss present a substantial economic burden to society, which includes
- A. the economic costs associated with diagnosis, treatment, and rehabilitation

- B. the economic costs associated with compensation
- C. social costs of disease as reflected by reduced quality of life, disability, and suffering
- D. all of the above
- E. both A and B

33. In the United States, the most common measure of the economic cost of occupational hearing loss is based on
- A. worker compensation costs
 - B. the costs of operating a hearing conservation program
 - C. the cost of implementing engineering controls
 - D. all of the above
34. In the United States, the overall economic costs associated with occupational hearing loss are tracked by
- A. NIOSH
 - B. OSHA
 - C. the Bureau of Labor Statistics
 - D. all of the above
 - E. none of the above

35. Within limits, the economic burden of occupational hearing loss
- A. may be estimated by calculating quality-adjusted life years
 - B. may be estimated by calculating disability-adjusted life years
 - C. may be estimated by using the contingent valuation method
 - D. all of the above
 - E. none of the above

Article Ten (pp. 182–185) Communication, Safety, and Warning Signal Interference

36. OSHA inspections following workplace fatalities
- A. provide safety personnel with statistics on the role noise and hearing loss played in the accident
 - B. determine if the use or nonuse of hearing protectors played a role in the accident

- C. do not involve an investigation of the role of noise as a contributing factor
 - D. both A and B
37. A worker's ability to hear and respond to a warning signal
- A. has been shown to be highly correlated with whether or not a worker believes his or her job is dangerous
 - B. has been shown to be positively correlated with stimulants such as caffeine and nicotine
 - C. involves complex relationships between the worker's hearing thresholds, background noise levels, and type of hearing protector
 - D. all of the above
38. Using double protection (i.e., both plugs and muffs)
- A. has been shown to slightly improve ability to localize a warning signal because the attenuation of external noise reduces distortions caused by "overdriving" the auditory system
 - B. has been shown to have no additional effect on localization beyond the effect incurred from wearing an earplug
 - C. has been shown to interfere so greatly with a worker's ability to localize a warning sound that OSHA issued a 2009 policy statement recommending double protection not be worn in noise levels below 90 dBA
 - D. none of the above
39. Wearing hearing protectors may
- A. improve a worker's ability to hear warning sounds and to communicate
 - B. interfere with a worker's ability to hear warning sounds and to communicate
 - C. have no significant influence on a worker's ability to localize the source of a sound, or may completely eliminate a worker's ability to locate the source of a sound

- D. A and B only
- E. all of the above

Article Eleven (pp. 186–187) Hearing-Critical Jobs

40. A hearing-critical job is defined as
- A. a job where, despite the presence of loud noise, the use of hearing protectors is prohibited in order to ensure that critical sounds are heard
 - B. a job 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
 - C. a job in which it has been determined that the need to hear critical sounds outweighs the need to utilize reasonable accommodations in order to hire a hearing impaired person; such jobs must be registered with the U.S. Department of Labor, and, where applicable, with a state's department or bureau of vocational rehabilitation
 - D. all of the above
 - E. both B and C
41. The criteria for identifying hearing-critical jobs
- A. are outlined in a nonmandatory appendix of the OSHA Hearing Conservation Amendment
 - B. are addressed in a mandatory appendix of the OSHA Hearing Conservation Amendment
 - C. were initially developed by the military and have since been standardized for use by most police and fire departments to hire new recruits
 - D. none of the above
42. Most criteria for identifying individuals qualified to work in a hearing-critical job involve
- A. pure-tone hearing thresholds
 - B. uncalibrated speech tests such as the whisper test

- C. pure-tone hearing thresholds and speech discrimination in quiet
- D. pure-tone hearing thresholds and speech intelligibility in noise
- E. both A and B

Article Twelve (pp. 188–189) Nonoccupational Noise Exposure

43. Results of recent population studies have shown
- A. little change in the hearing of young adults when compared to prior studies
 - B. the hearing of young adults to generally be worse today than in previous studies
 - C. the hearing of young adults to be slightly better today than in previous studies
 - D. mixed results with young women having better hearing and young men having worse hearing than previous studies
44. Loud music has been the subject of many studies. Some of the findings of these studies have shown that
- A. music is commonly played at levels loud enough to be hazardous
 - B. there is a high incidence of permanent threshold shift among musicians
 - C. there is a significant difference in the hearing levels between musicians who wear hearing protection and those who do not
 - D. all of the above
 - E. A and B only
45. Studies of off-work noise exposures (not including those who shot firearms) have shown that
- A. nonoccupational noise exposures were generally safe (i.e., below 80 dBA TWA)
 - B. nonoccupational noise exposures were mildly hazardous with the most common TWAs being between 80 and 85 dBA
 - C. there is a great difference in the weekday versus weekend nonoc-

cupational exposures, with week-day exposures most commonly below 70 dBA and weekend exposures most commonly between 85- and 90-dBA TWA

- D. individual nonoccupational exposures varied so greatly from day to day and between individuals that it is not possible to characterize nonoccupational exposures

Article Thirteen (pp. 190–192) Tinnitus

46. Tinnitus may have a number of causes.
- A. Therefore, it is not possible to claim someone's tinnitus is due to noise exposure.
 - B. Because tinnitus is strongly associated with retrocochlear lesions, tinnitus can be attributed to noise exposure only after magnetic resonance imaging has ruled out other causes.
 - C. However, if NIHL is present, there needs to be "strong contrary evidence for tinnitus to be diagnosed as due to something else."
 - D. None of the above is correct.
47. According to a 2005 Institute of Medicine report for patients with a history of noise exposure, which of the following is true?
- A. Tinnitus is most likely to develop when there is an asymmetrical vascular supply between different regions of the stria vascularis. How the vascular supply differs and the regions where this difference occurs is also thought to determine the subjective perception of the tinnitus.
 - B. Tinnitus occurs when etymotic apoptotic cellular degeneration within the organ of Corti allows the tectorial membrane to hyperstimulate adjacent residual stereocilia of the inner hair cells.
 - C. Tinnitus is highly associated with damage to Henson's pillars and the subsequent collapse of basal cells that support the organ of Corti. The region where this

occurs will have a flaccid basilar membrane that will cause hyperstimulation of hair cells in adjacent regions. The magnitude of the damage to Henson's pillars is thought to explain both the subjective loudness and pitch of the tinnitus.

- D. The effects of noise exposure and hearing loss disrupt the delicate balance between excitation and inhibition in the central auditory pathway, and the dorsal cochlear nucleus has been implicated as a possible generator site for tinnitus.
48. Studies have shown that the risk of developing tinnitus following noise exposure
- is greater for workers exposed to impulsive noise than for workers exposed to continuous noise
 - is greater for workers exposed to continuous noise than for workers exposed to impulsive noise
 - is no different for workers exposed to impulsive noise than for workers exposed to continuous noise
 - all of the above
49. Although tinnitus is often mentioned in the conduct of hearing conservation programs, which of the following is true?
- It is generally done in relation to establishing a basis for worker compensation.
 - It is generally done to support a determination of the work relatedness of a hearing loss.
 - 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
 - Both A and B are correct.
- Article Fourteen** (pp. 193–195) Extra-Auditory Effects of Noise
50. Which of the following is a true statement?
- Noise is considered a nonspecific biological stressor, and thus it can influence the entire physiologic system.
 - Noise is considered a specific biological stressor because it can affect specific physiologic systems.
 - Noise is considered a physical rather than a biological stressor because noise is a physical entity originating outside the body.
 - Noise is not considered to be a stressor because it does not act in the same way as other stressors that cause the body to go through a series of biological changes, preparing either to fight or to run away—the classic “fight-or-flight” response.
51. The evidence for extra-auditory effects
- is probably strongest for cardiovascular effects, such as increased blood pressure and changes in blood chemistry
 - is probably strongest for hormonal effects, even though these have largely been shown to be relevant primarily to males with respect to the positive association between high noise and elevated testosterone levels
 - is probably strongest for changes in neurotransmitters such as serotonin and tryptophan
 - is so contradictory that it is not possible to determine a causal relationship between noise and extra-auditory effects
52. Because the extra-auditory effects of noise are mediated by the auditory system
- the federal regulations and permissible exposure limits that apply to occupational noise exposure also apply to extra-auditory effects

- B. properly fitted hearing protection devices should reduce the likelihood of these effects in the same way they do for hearing loss.
- C. both A and B
- D. none of the above

Article Fifteen (pp. 210–212) Noise Measurement

53. Which of the following parameters is *not* used in calculating noise dose?
- A. Criterion level
 - B. Exchange rate
 - C. Hearing threshold
 - D. Time
54. According to a study by Smith et al, when is a task-based exposure assessment most accurate?
- A. Workers conduct a variety of nonroutine tasks.
 - B. Within-task variability is smaller than between task variability.
 - C. Detailed task definitions are not technically feasible.
 - D. Work tasks are broadly defined.
55. For workers whose shifts extend beyond 8 hours, the ACGIH recommends calculating cumulative dose over 7 consecutive days, and limiting any single daily dose to
- A. 100%
 - B. 200%
 - C. 300%
 - D. 500%

Article Sixteen (pp. 213–214) Noise Control

56. Engineering controls hold the primary place in the hierarchy of controls because
- A. they utilize the most advanced available technologies
 - B. the OSHA noise standard dictates that they should be the first line of defense against excessive noise exposure

- C. personal protection devices cannot reduce noise exposures below the PEL
- D. engineering controls protect everyone in a uniform manner

57. Studies have shown that reducing noise levels by just 5 to 10 dB is all that is needed to bring what percent of workers within the OSHA PEL?
- A. 90%
 - B. 95%
 - C. 99%
 - D. 100%
58. True or false? A significant barrier to implementation of noise control is lack of dissemination of the wide range of available noise control solutions.
59. All of the following factors have been identified as crucial to the successful implementation of engineering noise controls, *except*
- A. recognition of the need for noise control
 - B. availability of proven noise control technologies
 - C. substantial financial base to support control efforts
 - D. collaboration across government, industry, and other stakeholders

Article Seventeen (pp. 215–217) Hearing Protection Devices

60. In the United States, regulation of hearing protector labeling is managed by
- A. NIOSH
 - B. OSHA
 - C. Food and Drug Administration
 - D. EPA
61. Which of the following is a disadvantage of using the Microphone in Real Ear technique for measuring the attenuation of hearing protectors?
- A. It does not account for bone-conducted sound transmission.
 - B. It requires a response from the test subject.

- C. It cannot be used to evaluate level-dependent hearing protectors.
- D. It results in highly variable attenuation measurements.
62. A company purchases a case of hearing protectors for its noise-exposed employees. The Noise Reduction Rating of the hearing protector is 26. What percent of the employees are likely to achieve 26 dB of sound attenuation using this protector?
- 5%
 - 50%
 - 98%
 - 100%
63. The most important factor is selecting an appropriate hearing protector for a particular individual is the
- the labeled noise reduction rating
 - the cost of the device
 - the individual's perception of its comfort and wearability
 - the expected usable life of the protector

Article Eighteen (pp. 218–221)
Audiometric Monitoring

64. The purpose of audiometric monitoring of noise-exposed workers is to
- identify early signs of noise damage so intervention can occur before hearing is permanently damaged
 - document hearing threshold shifts for purposes of regulatory compliance
 - provide a record of hearing thresholds over the course of employment for workers' compensation claims
 - conduct surveillance of occupational hearing loss across industries
65. Although the ANSI requirements for maximum permissible noise during audiometric testing were considered unattainable at the time the OSHA regulation was written

- studies have shown that accurate threshold testing is possible in rooms that meet the OSHA noise criteria
- the OSHA standard has since been revised to reflect the most recent ANSI background noise standard
- recent research indicates that most industrial audiometric test rooms can meet the ANSI standard except at 500 Hz
- background noise levels are irrelevant in rooms in which multiple persons are tested simultaneously

66. True or false? Threshold shift criteria that make use of averaged thresholds are more sensitive to changes in hearing sensitivity than those that make use of individual thresholds.
67. Which of the following statements is true?
- Identification of temporary threshold shifts has been shown to be efficacious in preventing permanent threshold shifts.
 - There is no consensus on the definition of a "noise notch."
 - The OSHA age correction tables take into account the differing susceptibilities to threshold shift by race and gender.
 - OAEs may be a viable alternative to pure-tone thresholds for audiometric monitoring because they evaluate the auditory system as a whole.

Article Nineteen (pp. 222–225)
Training and Motivation

68. The strongest predictor of workplace safety behavior is generally
- factual knowledge of the ear and hearing
 - actual and perceived barriers to protective action
 - incentive programs for workplace safety
 - availability of protective equipment at the work site

69. Training programs must frame message appropriately based on key audience characteristics, which include all of the following *except*
- A. worker age and gender
 - B. ethnic and cultural background
 - C. noise exposure level
 - D. hearing thresholds

70. True or false? Most research indicates that hearing health programs are most effective when integrated into an overall health and safety program at the workplace.

71. A key topic that is missing from most training and motivation programs is
- A. the structure and function of the ear
 - B. mechanisms by which noise damage occurs
 - C. use of hearing protection devices to prevent work-related hearing loss
 - D. the critical importance of hearing to quality of life

Article Twenty (pp. 226–229) Special Populations

72. A worker population that may require special types of hearing protection is
- A. younger workers
 - B. non-English speaking workers
 - C. hearing-impaired workers
 - D. temporary workers

73. A worker population that may benefit from predicted noise exposure estimates based on existing noise data is
- A. young workers
 - B. mobile workers
 - C. Spanish-speaking workers
 - D. hearing-impaired workers

74. True or false? Foreign-born workers are disproportionately employed in jobs with hazardous noise exposure.

75. Possible accommodations for noise-exposed, hearing-impaired workers include
- A. flat attenuation hearing protection devices

- B. use of hearing aids under earmuffs
- C. visual alerting systems
- D. A and C only
- E. all of the above

76. Which of the following worker populations are not protected by any occupational noise exposure regulation?
- A. Employees under age 16
 - B. Construction workers
 - C. Certain federal and state employees
 - D. Temporary workers

Article Twenty-One (pp. 230–231) Record Keeping

77. Which of the following records should be integrated in a comprehensive record-keeping system for hearing loss prevention?

- A. Noise exposure data
- B. Hearing threshold data
- C. Demographics
- D. All of the above
- E. A and B only

78. Surveillance of occupational noise exposure and hearing loss is possible utilizing existing records maintained by hearing conservation programs. The missing component is

- A. a technologically feasible database structure
- B. ancillary data such as equipment calibration records
- C. consensus on data elements and variable definitions
- D. access to training on OSHA record-keeping procedures

79. Applying personal health record technology to hearing conservation practices would

- A. allow workers to maintain their audiometric test records as they move from employer to employer
- B. relieve employers of the responsibility of maintaining audiometric test records for individual employees

- C. meet OSHA regulatory criteria for record-keeping procedures in hearing conservation programs
- D. create a breach of confidentiality regarding audiometric test records

Article Twenty-Two (pp. 232–234)
Program Evaluation

80. OSHA regulations specify which evaluation metric for hearing loss prevention programs in general industry?
- A. Compliance checklist
 - B. Annual standard threshold shift (STS) rate below 3%
 - C. Audiometric database analysis
 - D. None of the above
81. Which of the following is the chief advantage to using the annual STS rate as a program evaluation criterion?
- A. It uses a metric already calculated as part of mandated hearing conservation activities.
 - B. It requires data to be accumulated over several years.
 - C. It is constant across age and length of employment.
 - D. It accounts for other relevant factors such as gender, race, and nonoccupational noise exposure.
82. Which of the following metrics could be used by any company, regardless of size, as one measure of hearing conservation program effectiveness?
- A. Audiometric database analysis
 - B. Rate of hearing loss among noise-exposed versus non-noise-exposed employees
 - C. Annual count of workers exposed above 85 dBA
 - D. All of the above
 - E. None of the above
83. True or false? As long as it is appropriately selected, one metric is sufficient to adequately assess a company's hearing loss prevention program.

Article Twenty-Three (pp. 235–237)
Treatment and Rehabilitation

84. True or false? Traditional aural rehabilitation programs are sufficient to meet the needs of workers who have sustained hearing loss due to noise exposure at work.
85. One approach that may help improve participation hearing-impaired workers in aural rehabilitation programs might be to
- A. hold the rehabilitation sessions in medical offices remote from the work site
 - B. schedule rehabilitation programs during working hours
 - C. train professionals with whom the workers are comfortable to conduct the rehabilitation program
 - D. focus the rehabilitation approach on hearing aid use and speech reading skills
86. Current pharmacological approaches to preventing or reversing noise-induced damage are oriented toward all the of following, *except*
- A. regeneration of hairs cells that have been damaged or destroyed
 - B. blocking the generation of reactive oxygen species and free radicals in cochlear cells
 - C. prevention of apoptosis
 - D. upregulation of growth hormones to prevent cell death
87. Pharmaceutical therapies for noise-induced hearing loss do not address
- A. reduction of free radicals in the inner ear
 - B. mechanical damage to cochlear structures
 - C. the molecular cascade that leads to cochlear cell death
 - D. all of the above

Article Twenty-Four (pp. 238–239)
Public Health Perspective

88. Despite over 30 years of occupational noise exposure regulations in the United States, NIHL remains one of the most prevalent occupational conditions. One possible reason could be
- A. lack on information on effective hearing loss prevention programs
 - B. social acceptability of loud noise in recreational environments
 - C. insufficient market supply of hearing protection devices
 - D. inaccurate data on the prevalence of workplace threshold shifts
89. A major weakness of the American Speech-Language-Hearing Association's multimillion dollar hearing health campaign featuring James Earl Jones in 2000 and 2001 was
- A. poor timing of the media campaign
 - B. inappropriate targeting of the campaign to identified audiences
 - C. insufficient national coverage of the television ads and radio spots
 - D. lack of published measures of the impact of the campaign
90. Social marketing, which has proven successful in producing healthy behaviors, involves
- A. integration of marketing principles with social-psychological theories of human behavior
 - B. encouraging behavior change through social media outlets such as Facebook and Twitter
 - C. marketing hearing protection devices in social arenas such as sporting events and concerts
 - D. none of the above

Article Twenty-Five (pp. 240–241)
Implementation

91. Which of the following strategies is *not* likely to improve effective implementation of hearing loss prevention programs?
- A. Collaboration with other professionals working in hearing conservation
 - B. Identification of barriers that workers perceive to hearing conservation
 - C. Publication of recommendations in scientific journals
 - D. Improved regulatory standards and enforcement
92. In its 2006 report on the NIOSH Hearing Loss Prevention Research program, the Institute of Medicine acknowledged the progress that NIOSH had made in developing engineering noise controls for the mining sector, but noted that these advances had not been carried over to other industries. The Institute concluded that this lack of knowledge transfer was due to
- A. the technical unsuitability of mining noise controls for other sectors
 - B. resistance of other sectors to noise control efforts
 - C. lack of funding to support technical transfer
 - D. failure to communicate the noise control solutions to other sectors
93. True or false? Hearing conservation professionals and noise-exposed workers have disconnected experiences that interfere with successful implementation of hearing loss prevention initiatives.

ANSWER SHEET

Circle the correct answer(s) to each question

National Research Agenda for the Prevention of Occupational Hearing Loss

VOLUME 34, NUMBER 3 2013 (1.5 CEU ASHA; 1.0 CEU AAA)

ARTICLE ONE

(page 147)

- 1. A B C D
- 2. A B C D
- 3. A B C D
- 4. True or False

ARTICLE TWO

(page 150)

- 5. A B C D E
- 6. A B C D
- 7. A B C D
- 8. A B C D E

ARTICLE THREE

(page 155)

- 9. A B C D E
- 10. A B C D
- 11. A B C D
- 12. A B C D

ARTICLE FOUR

(page 161)

- 13. A B C D
- 14. A B C D
- 15. A B C D
- 16. A B C D

ARTICLE FIVE

(page 165)

- 17. A B C D E
- 18. A B C D E
- 19. A B C D
- 20. A B C D E

ARTICLE SIX

(page 168)

- 21. A B C D E
- 22. A B C D E
- 23. A B C D
- 24. A B C D

ARTICLE SEVEN

(page 171)

- 25. A B C D E
- 26. A B C D
- 27. A B C D
- 28. A B C D

ARTICLE EIGHT

(page 174)

- 29. A B C D E
- 30. A B C D
- 31. A B C D

ARTICLE NINE

(page 176)

- 32. A B C D E
- 33. A B C D
- 34. A B C D E
- 35. A B C D E

ARTICLE TEN

(page 182)

- 36. A B C D
- 37. A B C D
- 38. A B C D
- 39. A B C D E

ARTICLE ELEVEN

(page 186)

- 40. A B C D E
- 41. A B C D
- 42. A B C D E

ARTICLE TWELVE

(page 188)

- 43. A B C D
- 44. A B C D E
- 45. A B C D

ARTICLE THIRTEEN

(page 190)

- 46. A B C D
- 47. A B C D
- 48. A B C D
- 49. A B C D

ARTICLE FOURTEEN

(page 193)

- 50. A B C D
- 51. A B C D
- 52. A B C D

ARTICLE FIFTEEN

(page 210)

- 53. A B C D
- 54. A B C D
- 55. A B C D

ARTICLE SIXTEEN*(page 213)*

56. A B C D
 57. A B C D
 58. True or False
 59. A B C D

ARTICLE SEVENTEEN*(page 215)*

60. A B C D
 61. A B C D
 62. A B C D
 63. A B C D

ARTICLE EIGHTEEN*(page 218)*

64. A B C D
 65. A B C D
 66. True or False
 67. A B C D

ARTICLE NINETEEN*(page 222)*

68. A B C D
 69. A B C D
 70. True or False
 71. A B C D

ARTICLE TWENTY*(page 226)*

72. A B C D
 73. A B C D
 74. True or False
 75. A B C D E
 76. A B C D

ARTICLE TWENTY-ONE*(page 230)*

77. A B C D E
 78. A B C D
 79. A B C D

ARTICLE TWENTY-TWO*(page 232)*

80. A B C D
 81. A B C D
 82. A B C D E
 83. True or False

ARTICLE TWENTY-THREE*(page 235)*

84. True or False
 85. A B C D
 86. A B C D
 87. A B C D

ARTICLE TWENTY-FOUR*(page 238)*

88. A B C D
 89. A B C D
 90. A B C D

ARTICLE TWENTY-FIVE*(page 240)*

91. A B C D
 92. A B C D
 93. True or False

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