18 Noise

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The connection between noise exposure and a decline in hearing ability has been known for centuries. Almost 2,000 years ago, Pliney the Elder noted that people living near noisy waterfalls exhibited an accelerated and progressive hearing loss (1). Ramazzini directed attention to noise as a workplace hazard by documenting cases of occupational deafness in the 1700s (2). Early workplace noise tended to be mostly intermittent impact noise from the pounding of metalworkers and carpenters and affected mostly those performing the hammering. The dawn of the Industrial Revolution introduced continuous noise to the workplace, and the effect on hearing extended beyond the workers operating the machine to all those in the area. Today, noise is the most prevalent workplace hazard in the world.

The Occupational Safety and Health Administration (OSHA) has estimated that more than 7.9 million manufacturing workers in the United States are occupationally exposed to noise greater than 80 dBA (3).[1] The Environmental Protection Agency (EPA) estimated that more than 9 million U.S. workers in manufacturing are exposed to noise levels of 85 dBA or higher (4). Neither estimate included an additional 3 million workers employed in agriculture, mining, construction, transportation, or the federal government. More than 1 million workers in the U.S. manufacturing sector experience hearing loss from occupational noise, with half of them having moderate to severe hearing impairment (5). One worker in four exposed to 90 dBA noise over a working lifetime will develop a hearing loss that can be attributed to occupational noise exposure (6).

The largest number of workers exposed to levels of noise that are potentially damaging to their hearing are employed in manufacturing (7). Surveys indicate that more than half of industrial machines emit noise levels between 90 and 100 dB, and approximately 50% of industrial work environments have noise levels between 85 and 95 dB. Fewer than 6% of the machines surveyed produced noise levels lower than 85 dB (8).

Despite the prominence of noise in manufacturing, significant numbers of people in other industrial sectors (e.g., construction, agriculture, mining, transportation, the military) are exposed to hazardous noise (7–9). Studies indicate that, given the same noise exposures, women are less susceptible to noise-induced hearing loss than men, and African-Americans are less susceptible than Caucasians. The left ear shows a tendency to be more susceptible than the right to the effects of noise (10,11).

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[1] A common unit for measuring sound is the decibel (dB). Occupational noise is often assessed using a nonlinear filter (A-scale). The intensity of noise measured using the A scale is recorded as dBA.

The purposes of this chapter are to provide an overview of occupational noise and its effects on the ear and hearing and to review regulations and recommendations for effective programs to prevent job-related hearing loss. Although this chapter focuses on occupational noise-induced hearing loss and the consequences of excessive noise exposure, it should noted that workplace chemicals also can cause hearing loss (12,13); that increased mechanization has caused hearing loss from noise in the recreational, community, and home environments (14); that hearing loss occurs with aging (presbycusis) (15); and that noise can induce nonauditory effects (e.g., elevation of blood pressure, sleep disruption, stress, altered work performance) (16,17).

PROPERTIES OF SOUND AND NOISE

What we perceive as sound is the result of rapid fluctuations in the ambient air pressure caused by a vibrating object or a sudden expansion of gases, such as occurs in an explosion. These fluctuations in air pressure are called *sound waves* or *sound pressure.* Sound pressure waves are characterized by amplitude (loudness), frequency (pitch), and temporal pattern (18,19). The amplitude, measured in decibels (dB), represents the magnitude of change in the sound pressure wave relative to the ambient air pressure or a reference pressure. Human beings have an operational range up to approximately 130 dB before immediate damage results. The frequency, measured in hertz (Hz), is the speed with which the changes in the ambient air pressure occur per second. Humans perceive frequencies between 20 and 20,000 Hz. Amplitude and frequency may vary independently of one another. A pure tone is defined by a fixed frequency (e.g., 1,000 Hz) but may vary in amplitude. The temporal variations of these acoustic properties permit us to distinguish one sound from another and are the basis for our categorization of sounds as desirable or undesirable.

Noise generally comprises many pure-tone frequencies that interact with one another to yield a sound with a complex mixture of loudness and pitch. A given noise with a relatively constant intensity is called *continuous* or *steady-state* noise. If a noise has occasional drops in intensity it may be referred to as *fluctuating* or *interrupted* noise. Noise characterized by a sudden rise followed by a decay in its intensity is referred to as *impact* or *impulse* noise.

The decibel (dB), the common unit for measuring the intensity of the noise or its sound pressure level (SPL), reflects the log of the ratio between the measured SPL, $p_{(1)}$, and a reference SPL, $p_{(0)}$. The reference SPL (0.0002 dynes/cm^2) is the approximate lowest SPL that can be detected by the human ear. Consequently, SPL in decibels is a measure of decibels above 0.0002 dynes/cm^2. The formula for calculating a decibel SPL is:

$$SPL = 20 \log [p_{(1)}/p_{(0)}]$$

THE AUDITORY SYSTEM

The human peripheral auditory system can be divided into three parts: the external ear, the middle ear, and the internal ear (Fig. 18-1). The external ear consists of the auricle (which is often referred to as "the ear") and the external auditory meatus (ear canal). The middle ear is made up of the eardrum, the ossicles (three small bones), a number of suspension ligaments, two small muscles, the middle ear cavity, and the eustachian tube. The internal ear is the cochlea, which contains the sensory cells for detecting sound. This peripheral auditory system connects to the central auditory system, which consists of the eighth cranial nerve, the auditory pathways in the brain stem, and the auditory areas of the brain (19–21).

External Ear

Unlike animals with mobile pinnas, the human auricle does not play a major role in hearing or sound localization. The ear canal allows the more delicate structures of the auditory system to be recessed in the protec-

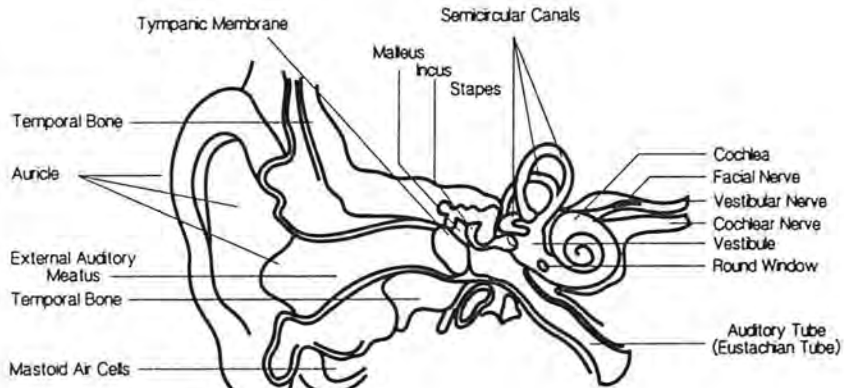

FIG. 18-1. Schematic drawing of the ear.

tive temporal bone of the skull. This part of the skull is the densest bone in the human body. The ear canal, somewhat like a cave, provides a stable temperature and humidity for the tissue paper–thin eardrum that seals its medial end. A very important characteristic of the ear canal is that, like any tube that is open on just one end, it has a resonant frequency. The resonance enhances the transmission of acoustic energy by approximately 15 to 20 dB for frequencies between 2,000 and 3,000 Hz and contributes to the fact that human auditory sensitivity is greatest for these frequencies.

Middle Ear

The principal role of the middle ear is to serve as an impedance matching and transmission device between the airborne acoustic vibrations in the ear canal and the fluid-filled cochlea.

The eardrum consists of a fibrous layer sandwiched between an outer dermal layer and an inner mucosal layer. A nonpathologic eardrum is transparent and permits visualization of middle ear structures. Sound waves traveling down the ear canal strike the eardrum and set it vibrating. These vibrations are transmitted to the ossicles (malleus, incus, and stapes), which are suspended in the middle ear cavity by ligaments. These are the smallest bones in the human body and remain constant in size throughout life. The two smallest muscles in the human body (tensor tympani and stapedius) attach to the ossicles and, on contraction, reduce the amount of sound energy transmitted through the middle ear. The contraction of the tensor tympani and stapedius (acoustic reflex) can be triggered by sudden loud sounds, but this does not occur rapidly enough to prevent all the damaging energy produced by an impulsive noise.

The medial end of the stapes bone (the footplate) is attached to the fluid-filled cochlea. The eardrum is much larger than the footplate of the stapes; this results in improved energy transmission through the middle ear (area ratio). In addition, there is a difference between the long arm of the malleus and the long arm of the incus, which, like a crowbar, provides increased transmission of mechanical vibrations through the middle ear through a lever action. The area ratio and lever principle enhance the transmission of vibrations in the air of the ear canal to the fluid of the cochlea by as much as 30 dB. As a result of the external and middle ear, some sound transmissions are enhanced by as much as 50 dB. The eustachian tube connects the middle ear cavity and the upper throat cavity and serves to equalize pressure in the middle ear cavity with the external barometric pressure (e.g., when elevators or planes ascend or descend).

Muscles attached to the eustachian tube cause it to open during swallowing and yawning.

Internal Ear

The main function of the cochlea is to transduce mechanical vibrations in its fluid, generated by the stapes footplate, to neurally coded electrical impulses that are transmitted to the brain. The human cochlea has one row of inner hair cells and three to five rows of outer hair cells—a total of 20,000 to 25,000 hair cells. These hair cells sit on the basilar membrane, which vibrates in response to the pressure waves generated in the cochlear fluid. These mechanical movements produce an excitation of the sensory cells that causes them to stimulate neural fibers leading to the brain. The outer rows of hair cells have sometimes been considered the source of sensitivity for very-low-intensity sounds near the hearing threshold.

The rows of hair cells run the length of the cochlea. The hair cells responding to higher-frequency sounds are located nearer the basal end of the cochlea, where the footplate of the stapes is located, and the hair cells more sensitive to lower-frequency sounds are found more toward the opposite (apical) end of the cochlea. The spatial (tonotopic) differentiation of frequency coding in the cochlea is found also in the auditory pathways of the brain stem and the projections of the auditory system at cortical levels.

NOISE-INDUCED HEARING LOSS

Usually noise-induced hearing loss develops gradually as a result of damage to the sensory hair cells in the cochlea from prolonged loud exposures. The relative hazard to hearing from exposure to continuous, interrupted, impact or impulse noise depends on the intensity, duration, and frequency composition of the noise. Metabolic exhaustion and mechanical injury are the presumed mechanisms underlying cochlear damage from noise exposure. In metabolic exhaustion, the sensory cells are unable to keep pace with the energy demands placed on them. Most exposures to noise lack sufficient intensity or duration to result in immediate permanent damage to the auditory system. At these subtraumatic doses, metabolic exhaustion causes the auditory system to exhibit a temporary shift in hearing sensitivity that returns to normal with sufficient rest from noise exposure. However, repeated metabolic stress can result in damage or destruction of auditory hair cells and a permanent loss of hearing (22).

Mechanical stress on hair cells is thought to occur at higher noise levels and to result from a physical breakdown in cell structures caused by excessive vibratory forces transmitted into the cochlear fluids and basilar membrane by the stapes footplate (23–26). Noise exposures that tax cells' metabolic equilibrium can increase the their susceptibility to mechanical damage. The metabolic state of the hair cells is correlated with their ability to withstand or recover from physical stress.

Once the sensory hair cells that respond to a given frequency are destroyed, sounds at that frequency are no longer heard. Destroyed hair cells cannot repair themselves, nor can medical procedures restore normal function. Hair cell damage from noise usually affects the rows of outer hair cells before damaging the inner hair cells. Although the outer hair cells are more susceptible to damage from noise, the loss of an equal number of inner hair cells results in a much greater deficit in hearing.

Hair cells in the basal turn of the cochlea—those that respond to the higher-frequency tones—are more susceptible to noise-induced damage than are hair cells in the apical end of the cochlea. As a result, the early stages of noise-induced hearing loss usually are characterized by decreased ability to hear very soft, higher-frequency sounds. A common sign of noise-induced hearing loss is a greater decline in hearing acuity for tones between 4,000 and 6,000 Hz. The locus of damage to the hair cells along the basilar membrane is related to the physical properties of the noise. In most cases, the hearing loss is not perceptible in the early stages and may only be detected by audiometric tests. However, with continued overexposure to noise, the loss of sensitivity spreads from the higher frequencies into the speech frequencies (1,000 to 3,000 Hz). Once this occurs, considerable hearing loss already exists, and the ability to communicate or hear necessary sounds is significantly reduced.

The external or middle ear structures are damaged only by extremely intense noise, such as an explosive discharge. Severe damage to the external and middle ear can produce a reduction in hearing sensitivity of much as 30 to 50 dB as a result of loss of efficient transfer of sounds to the auditory sensory cells.

PREVENTING NOISE-INDUCED HEARING LOSS

Role of Government

Under the mandate of the 1970 Occupational Safety and Health Act, OSHA promulgated the 1971 noise standard for manufacturing companies engaged in interstate commerce (27). The 1971 noise standard covers most of manufacturing but does not cover workers in transportation, agriculture, construction, mining, or oil and gas servicing or drilling. However, mining is covered by noise standards enforced by the Mine Safety and Health Administration. Each of the enforced noise regulations incorporates an exposure limit based on a 90-dBA exposure for a duration of 8 hours with a 5-dB trading ratio. These noise standards also limit impulse noise to a peak SPL of 140 dB.

1971 Noise Standard

The 1971 noise standard requires that workers not be exposed to noise in excess of a 90-dBA time-weighted average (TWA) for 8 hours. The TWA is the average of the various exposure levels that occur during a period of measurement. Measurements are made using "the slow response" on the sound level meter. Higher dBA levels are permitted (not to exceed 115 dBA), but each increase of 5 dBA reduces the permitted exposure time by 50%; for example, 95 dBA for 4 hours or 100 dBA for 2 hours. This relation between noise level and exposure time is referred to as the 5-dB trading ratio or exchange rate; Table 18-1 gives an expanded list of allowable noise exposures. The OSHA noise regulation called for an "effective hearing conservation program" but does not specify the components of such a program. Exposure to impulse or impact noise is limited to peak pressures of 140 dB.

TABLE 18-1. *Permissible noise exposures*

Duration per day (hr)	Sound level (dBA slow response)
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25 or less	115

In 1983, based on the criteria for noise exposure recommended by the National Institute for Occupational Safety and Health (NIOSH) in 1971 (6), OSHA amended the 1971 noise standard. The 1983 amendment includes details of the components of a hearing conservation program and requires that a program be initiated when worker noise exposures exceed 85 dBA TWA. The OSHA-mandated hearing conservation program includes monitoring of noise exposure, periodic hearing testing of noise-exposed workers, noise abatement and/or administrative controls, provision of hearing protectors to employees, an employee education program, and record keeping (28).

Monitoring of Noise Exposure

The employer is required to identify workers whose noise exposure exceeds the limits defined in the 1971 noise standard. The identification of work areas with potentially hazardous noise levels is accomplished by assessing and monitoring noise levels. The noise data are reviewed as part of the process for determining compliance with noise regulations. Workers have the right to observe, or have a representative observe, the noise assessment procedures. Assessment of the noise exposure may be accomplished with the use of basic sound level meters, noise dosimeters, integrating sound level meters, or graphic level recorders (23). Measurement of noise with a sound level meter is appropriate when the levels are relatively steady and when the worker has a relatively stationary job. However, a noise dosimeter is required when noise levels are intermittent, vary greatly, or include impulse or impact noise. Many dosimeters offer options such as calculated dose for 3-dB or 5-dB exchange rates and selection of 8-hour criterion levels from 80 to 90 dBA.

As a general rule of thumb, potentially hazardous noise levels can be assumed to be present and hearing loss prevention strategies should be used if verbal communication is difficult at arm's length because of noise. However, decisions regarding which specific hearing loss prevention strategies to use require more objective assessments of the noise. Novices often are deceived into thinking that they can make accurate noise measurements because the devices appear simple to use: just point and note the position of the needle or digital readout. However, there are many variables and variations in the characteristics of both the physical environment (e.g., reverberation) and the measurement device (e.g., microphone selection, weighting, speed setting) that influence the accuracy of noise measurements. As the application of the noise data increases in importance (e.g., making decisions about effective engineering controls, developing a precise work area noise map, or determining whether permissible noise exposures are being exceeded), the services of professionals with training and experience in noise measurement should be obtained.

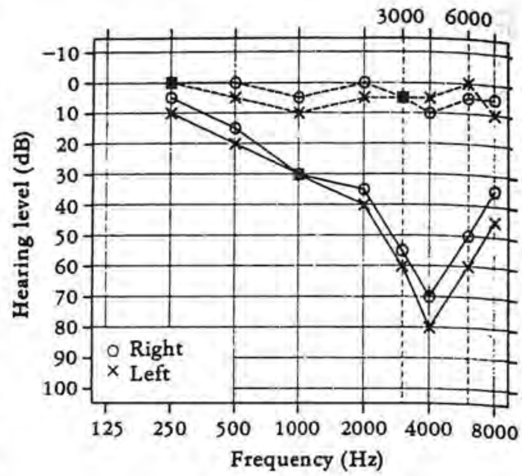

FIG. 18-2. An example of a typical audiogram from a person with normal hearing (*dashed lines*) and a person with bilateral sensorineural hearing loss resulting from excessive noise exposure. Note the maximum loss at 4,000 Hz and the spread of loss to the lower frequencies. (Audiogram provided by Robert I. Davis and Roger P. Hamernik.)

Periodic Hearing Tests

Hearing testing must be provided annually, at no cost, to workers exposed to 85 dBA TWA or more (Fig. 18-2). Specific procedures are explained for daily, yearly, and biannual audiometer calibration. Audiometry must be provided by a tester (audiologist, physician, or technician) or supervised by an audiologist, or an otolaryngologist, or other physician. Initial audiograms serve as a baseline reference against which subsequent audiograms are compared. An average shift of 10 dB at 2,000, 3,000, and 4,000 Hz is referred to as a standard threshold shift (STS). If an STS is determined to have occurred, the worker must be notified in writing of the STS, be retrained in the use of hearing protectors, and be refitted with hearing protectors.

Noise Abatement and Administrative Controls

Feasible engineering controls are required by the standard, but there is no clear definition of "feasible." Noise abatement encompasses efforts to reduce the workers' total noise exposure by means other than hearing protectors or to reduce the ambient noise. Administrative controls include actions such as locating lunch or break areas away from the noise or rotating workers out of noisy areas to reduce their total noise exposure. Although noise abatement and administrative controls require ingenuity and consideration for the specific conditions at a given work site, these approaches clearly reduce worker noise exposure and therefore are preferable to the less predictable performance of hearing protectors (24).

Hearing Protectors

Hearing protectors must be provided, at no cost to workers, before baseline audiometry if their noise exposure exceeds 85 dBA TWA or the allowable noise exposures, or if the worker experiences an STS (Fig. 18-3). The employee must be allowed to select from a variety of hearing protectors that reduce the occupational noise to exposures permitted by the noise standard. If an STS occurs, a hearing protector that reduces the noise exposure to 85 dBA TWA or less must be used.

FIG. 18-3. Many workers are exposed to loud noise at work. This fender stamping press operator at an auto parts plant in Michigan wears ear muffs to reduce his noise exposure. Noise production in a stamping operation may be difficult to control at the source. (Photograph by Earl Dotter.)

Employee Education

All employees mandated to be in the hearing conservation program are required to receive education annually concerning the effects of noise on hearing, the purpose of audiometric testing, and the use of personal hearing protection.

Record Keeping

Records must be kept of noise assessments (for 2 years) and results of audiometric tests (for the period of employment). These records must be made available, on request, to employees or their representatives. The records are to be transferred to, and maintained by, new owners of a company.

1998 NIOSH Recommended Criteria for Noise Exposure

NIOSH reviewed its 1971 recommendations regarding noise exposure and hearing conservation in the light of data and research that was published after 1971. In 1998, NIOSH generated a new recommendation on noise exposure that focused on hearing loss prevention (avoiding a hearing loss) rather than hearing conservation (limiting the amount of hearing loss) (29). The new recommendation maintains the 85-dBA, 8-hour limit, but replaces the 5-dB trading ratio with a 3-dB trading ratio (exchange rate). There are substantial scientific data to support the 3-dB exchange rate; it is used by the military and by most industrialized countries.

There are numerous differences among the 1998 NIOSH noise recommendations, the 1971 NIOSH noise recommendations, and the OSHA noise standards of 1971 and 1983. The following section highlights aspects of the 1998 noise recommendations that differ from previous U.S. regulations or recommendations. However, the OSHA noise standard is still the enforced noise regulation.

Recommended Exposure Limit

The NIOSH recommended exposure limit (REL) for occupational noise exposure is 85 dBA, as an 8-hour TWA with a 3-dB exchange rate. Greater exposures are considered hazardous.

Audiometric Evaluation and Monitoring

NIOSH recommends pure-tone air-conduction threshold testing of each ear at 500, 1,000, 2,000, 3,000, 4,000, and 6,000 Hz. Testing at 8,000 Hz should be considered, because it may be beneficial in determining the cause of a hearing loss. A baseline audiogram (after 12 hours away from noise) should be obtained before employment or within 30 days of enrollment in the hearing loss prevention program (HLPP). However, the annual monitoring audiogram should be obtained during or at the end of the work shift. If efforts to prevent overexposure to noise are inadequate, the worker may show a temporary change in hearing and this change can serve as an alert to take action on behalf of the employee or to correct aspects of the HLPP.

The new proposal for a sentinel audiometric event is an STS, defined as a decrease in hearing ability of 15 dB or more at any required audiometric test frequency in either ear that is confirmed on retest. NIOSH does not recommend the use of age correction tables when determining whether an STS has occurred. The age correction data are group statistics that inappropriately evaluate the effect of aging on the hearing of anyone above or below the mean.

Hearing Protectors

NIOSH recommends mandatory provision of hearing protectors for employees exposed to an 8-hour, 85-dBA TWA or greater. If the exposure exceeds an 8-hour, 100-dBA TWA, a combination of ear plugs and ear muffs is suggested. The effective noise attenuation of the hearing protectors selected should reduce exposure below 85 dBA TWA for 8 hours. To determine the effective noise attenuation of a protector, one can use a subject fit method, or the current manufacturer's noise reduction rating for the protector can be derated (i.e., subtract 25% for ear muffs, subtract 50% for slow-recovery formable ear plugs, and subtract 70% for all other ear plugs).

Monitoring Hearing Loss Prevention Program Effectiveness

The effectiveness of an HLPP should be monitored in terms of both the hearing loss prevented for the individual employee and the overall rate of noise-induced hearing loss for the population of employees. For the individual worker, the comparison of the current monitoring audiogram with the baseline audiogram determines whether hearing loss has been prevented. Annual review of the worker's audiometric profile is probably the best quality assurance check for small programs.

It is advisable also to monitor trends in audiometric data for the overall population of employees in large HLPPs. High variability in sequential audiograms indicates a lack of integrity for the hearing data and suggests a need to improve the quality of audiometric test procedures, equipment calibration, or record keeping. NIOSH recommends comparing the incidence of STS among the monitored employees with the incidence found in workers not exposed to noise. NIOSH also recommends careful evaluation of the HLPP if the STS incidence considered significant for the noise-exposed population is 3% greater than the incidence found in a nonexposed population.

Role of Providers of Hearing Loss Prevention Services

Audiologists, industrial hygienists, and health care providers are called on to evaluate or make recommendations regarding hearing loss prevention programs. A common approach to this task is to review and cite the federal regulations concerning hearing conservation programs. Such a review results in identifying the major components of a hearing conservation program. However, meeting the minimal requirements for a hearing conservation program does not guarantee that the program is effective in protecting workers against hearing loss.

An effective HLPP is the result of careful planning and continuous monitoring to ensure that the goal of hearing loss prevention is reached. The employer cannot accomplish this goal alone. It is necessary to have the support of everyone concerned with worker safety, including workers, unions, and trade organizations. The full commitment of the employer to the HLPP is necessary to ensure that the program is effective. Commitment to effective hearing loss prevention is vital to obtaining the level of employee motivation, active participation, and communication that is necessary if the program is to be a success. The employer's commitment is evidenced by establishment and support of key policies that promote the effectiveness of the HLLP (30–33).

Advisors on safety and health have a unique opportunity to encourage company administrators to establish policies that will promote effective HLPPs. The employer should strive for excellence in the HLPP and not simply meet minimal requirements set forth by state or federal regulations.

It is important to integrate the HLPP fully into the total safety program. There are several benefits to this approach. First, the safety officer can combine several safety programs into the time allotted for educating and motivating workers. Separate safety programs often result in workers' weighing the relative importance of one program against another. Often, hearing safety is not regarded as being as important as those safety programs already in place to prevent immediate and observable injuries such as burns, lacerations, or poisoning. Hearing loss occurs without pain, and it is not as immediate or dramatic as some other injuries.

In addition, the worker should be encouraged to use good hearing safety practices away from the job. There is growing evidence that when an effective HLPP reduces the hazard of workplace noise, much of a worker's hearing loss can be attributed to nonoccupational noise exposures (34–36). Making hearing protection available for off-the-job activities is one way to encourage good hearing safety outside the workplace.

Although an effective HLPP requires the full cooperation and participation of managers and workers, there should be one person (possibly assisted by a support team) who is responsible for ensuring the quality of the hearing conservation program. That person must serve as both a contact for all groups and a program coordinator. Absence of a contact person often leads to the perception that the employer is not committed to the HLPP and that the program really is not important. Physicians, nurses, safety officers, and union representatives frequently make good key personnel because their other activities generally involve contact and interaction with workers or committees.

Another policy should be to strive for simplicity and continuity in the HLPP. The more difficult it is for employees to understand and follow the rules, the more difficult it will be for employer to monitor the hearing conservation program.

The employer should have a policy of reviewing the program at regular intervals to determine whether the desired results are being obtained. The purpose of the periodic review is to identify problems and take corrective action. Consequently, there should also be a policy that requires careful modification of a program that does not adequately protect the employees.

There are many intangibles that are important to the success of an HLPP. Intangibles such as commitment, motivation, and continuity should not be overlooked when establishing or monitoring such a program. A sincere commitment by management to the key policies needed for a high-quality safety program, along with basic hearing loss prevention practices, usually results in successful incorporation of these intangibles into an effective HLPP.

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Occupational Health

Recognizing and Preventing Work-Related Disease and Injury

Fourth Edition

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