Chapter 7

NOISE AND THE IMPAIRMENT OF HEARING

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INTRODUCTION

Occupational health professionals must understand both the auditory effects of noise and the proper administration and philosophy of the U.S. Army's Hearing Conservation Program to protect personnel from noise-induced hearing loss.

Casual observers of auditory physiology and hearing science assume that the effects of noise on the auditory system are well understood. Unfortunately, this is far from the truth because the auditory mechanism is startlingly complex. Advances in medical technology are only now allowing us to elucidate the morphology and the function of the structures of the normal ear. Theories on the etiology of noise-induced auditory damage are continually evolved and redefined as anatomical examination and electrophysiological-measurement techniques of auditory structures improve. For example, our understanding of the effects of noise on hair cell stereocilia, hair cell synapses, the cochlear vascular supply, and the central auditory pathways are still emerging.[1] Nuances regarding noise-induced hearing loss that are not yet understood are more numerous than the concepts that are universally accepted. Details of the unknowns will not influence a practicing physician's ability to identify or treat a clinical hearing loss. Yet, an understanding of the facts should greatly assist the physician in the evaluation of cochlear function following a soldier's or worker's exposure to high-intensity (ie, loud) sound. The physician's clinical tool is the audiogram, which depicts the hearing ability of the examinee in frequencies (measured in hertz [Hz]) and intensities (measured in decibel [dB] hearing threshold levels [HTL]).

Preserving a person's ability to hear low-intensity (ie, soft) sounds or speech on the battlefield is of utmost importance to the fighting efficiency and safety of soldiers:

> When you prepare to fight, you must prepare to talk. You must learn that speech will help save your situation. You must be alert at all times to let others know what is happening to you. You must use your brain and your voice any time that any word of yours will help you or others. You are a tactical unit and you must think of yourself that way. Don't try to win a war or capture a hill all by yourself. Your action alone means nothing, or at best, very little. It is when you talk to others and they join with you that your action becomes important.[2(p137)]

But, as is often the case, while the soldier's ability to speak on the battlefield is recognized, the second half of the communication equation—the ability to hear—is not. Sensitive hearing cannot be taken for granted in the army. Good hearing is particularly important when vision is limited—in sentry duty and night patrols—or during communication over noisy electronic systems.

Hazardous noise pervades the military environment; a soldier's ability to hear can be assaulted and damaged permanently even before basic training is completed. Most noise-induced hearing loss occurs during routine training exercises and therefore should be almost completely preventable.[3] The need to conserve hearing is especially important during practice and test firings for soldiers who soon afterwards must rely on their hearing to detect the enemy and to perform other communication requirements of the mission. The increasing demand for weapons systems with greater speed, range, and firepower confounds the problem with higher and more-hazardous noise intensities.

In addition, military-industrial operations (which may include the manufacturing, maintenance, and testing of military ordnance) can also include noise hazards for both military and civilian personnel. Except for large-caliber weapons testing, most military-industrial activities have counterparts in the private sector.

AUDITORY SENSATION

The transmission of sound through the ear (Figure 7-1) involves a series of energy conversions. When sound waves enter the ear canal, the tympanic membrane is set into vibration. At this point, acoustic energy is converted into mechanical energy. The vibrations of the tympanic membrane are then transferred through the ossicular chain of the middle ear to the inner ear. The process of articulation between the tympanic membrane, the malleus, the incus, and the stapes converts mechanical energy into hydraulic energy. The final conversion of energy occurs at the level of the receptor cells of hearing, the hair cells, with the release of the neurotransmitter substances that initiate a chemoelectrical electrical impulse.

A brief review of auditory anatomy, which emphasizes the inner ear and cochlear mechanics, will help to familiarize readers with the complex mechanisms of auditory injury.

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Fig. 7-1. The external, middle, and inner ears in man. Reprinted with permission from Otologic diagnosis and treatment of deafness. *Clinical Symposia.* 1970;22(2):38. Slide 1161. West Caldwell, NJ: CIBA-GEIGY.

Fig. 7-2. Panel A is a low-power view of the osseous and membranous labyrinths. The cochlea is on the left. Panel B is a transverse section through the cochlea showing its three fluid-filled channels and the organ of Corti. The stria vascularis (not shown) is found on the spiral ligament at the outer circumference of the cochlear duct. Panel C is a high-power view that shows the constituent cells of the organ of Corti Reprinted with permission from Netter FH. The CIBA collection of medical illustrations. Vol 1. *Nervous System.* Part 1, *Anatomy and Physiology.* West Caldwell, NJ: CIBA-Geigy; 1987: 176. Slide 3132.

Auditory Anatomy

The cochlea, or inner ear (Figure 7-2), a fluid-filled medium that measures approximately 1 cm wide and 5 mm long in humans, has 2.75 turns. It is separated into three channels by the bony labyrinth, the basilar membrane, and the Reissner membrane. The uppermost channel—the scala vestibuli—and the lowermost channel—the scala tympani—are filled with perilymph, a fluid with a high concentration of sodium and a low concentration of potassium. Perilymph resembles normal extracellular fluid in composition and is near ground electrical potential. The medial channel—the scala media, also known as the cochlear duct—is located between the basilar and the Reissner membranes. This channel is filled with endolymph, a fluid with high potassium and low sodium concentrations. Endolymph resembles intracellular fluid and has a positive electrical potential. Within the scala media, the organ of Corti rests on the basilar membrane. The stria vascularis, a highly vascularized layer of tissue, lines the outer wall of the cochlea (on the surface of the spiral ligament) and has a significant function in the production of endolymph.

The organ of Corti, which contains the hair cells, supporting cells, and neural connections, is the key organ of hearing. It contains one row of approximately 3,400 inner hair cells, and three to five rows of outer hair cells totaling approximately 13,400 outer hair cells.[4] Cilia on the hair cells are arranged in visually distinct patterns (Figure 7-3): those on the inner hair cells form a nearly straight row (Figure 7-4), and those on the outer hair cells form a W-shaped pattern (Figure 7-5). The longer cilia on the outer hair cells are embedded firmly in the tectorial membrane, while the cilia on the inner hair cells are not embedded and may only attach loosely to the undersurface of the tectorial membrane.[5]

The cochlea is innervated by both afferent and efferent neural fibers. Humans have approximately 18,000 cochlear afferent fibers; 95% of them innervate the inner hair cells and only 5% innervate the more numerous outer hair cells. The inner hair cells have a divergent innervation pattern, in which each inner hair cell is innervated by many fibers. The outer hair cells have a convergent system, in which one nerve fiber innervates many outer hair cells. The cell morphology, neural innervation, and auditory functions of inner and outer hair cells are quite different. In

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Fig. 7-3. A scanning-electron micrograph of the upper surface of the organ of Corti with the tectorial membrane removed. There are three rows of outer hair cells and one row of inner hair cells. Reprinted with permission from Pickles JO. *An Introduction to the Physiology of Hearing.* New York: Academic Press; 1982. © 1982, Academic Press, Orlando, Fla.

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Fig. 7-4. The stereocilia on the inner hair cells form a visually distinct straight row. Reprinted with permission from Pickles JO. *An Introduction to the Physiology of Hearing*. New York: Academic Press; 1982. © 1982, Academic Press, Orlando, Fla.

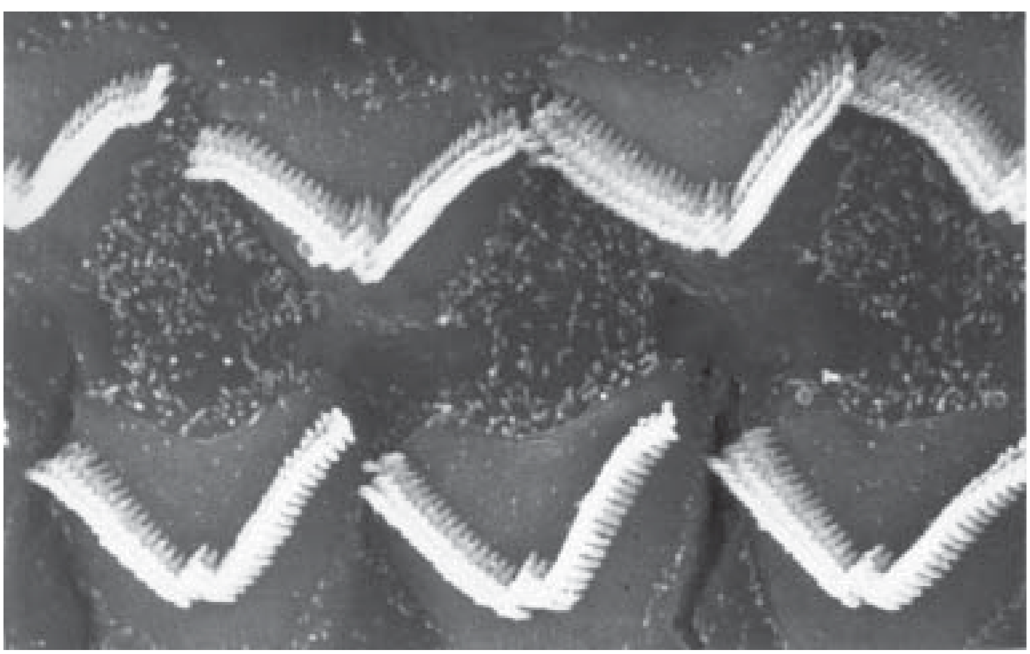

Fig. 7-5. The stereocilia on outer hair cells are smaller and form a visually distinct "V" or "W" configuration. Photograph: Courtesy of Donald Robertson, Perth, Australia.

general, audiologists believe that the outer hair cells' activities are summed together to provide increased auditory sensitivity, while the inner hair cells' activities provide fine discrimination.

Cochlear Mechanics

Mechanical movement of the stapes at the oval window creates a fluid-pressure wave in the inner ear, and the round window of the scala tympani acts as the release outlet for the pressure wave. Because liquid is an incompressible medium, this dichotomy of the oval and round windows allows a pressure wave to displace the basilar membrane. The location and amplitude of this displacement depend on the spectral components (ie, the frequency and the intensity combinations) of the stimulus.

The pressure wave creates movement of the organ of Corti on the basilar membrane with respect to the tectorial membrane. Because the tectorial membrane is anchored differently than the basilar membrane, a shearing motion is created between the two structures (tectorial membrane and the organ of Corti), which results in the mechanical displacement of hair cell cilia (Figure 7-6). The movement of the cilia alters the electrical resistance of the hair cell membrane: the resulting ion current flow through the membrane changes the resting voltage of the hair cell. The movement of the cilia initiates the release of neurotransmitter substance at the base of the receptor cell and prompts the neuroelectrical transmission of the signal.

The auditory system analyzes low frequencies (those below 1500 Hz) and high frequencies (those above 1500 Hz) differently (Figure 7-7). During sound stimulation, the frequency of the stimulus determines the site of maximal displacement of the basilar membrane. High frequencies stimulate the basal portion of the basilar membrane nearest the oval window, with rapidly decaying displacement. The higher the frequency, the closer the hair cell receptors to the oval window. Low-frequency sounds cause wider areas of displacement and stimulate a much larger area of the cochlea; maximum displacement of the basilar membrane occurs at its apical (upper) end. Physical characteristics of the basilar membrane, most notably its increased width and reduced stiffness at the apical end, determine the resonant properties of the basilar membrane. The frequency-dependent points of maximum displacement along the basilar membrane are dictated by these physical characteristics.

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Fig. 7-6. Relationship between the tectorial membrane and cilia of outer hair cells. At rest, (lower illustration) the cilia stand perpendicular to the tectorial membrane surface of the cell. When pressure waves move the basilar membrane, a shearing force acts to alter the angle of the cilia with respect to the tectorial membrane. Note that cilia of the inner hair cells are shown to bend, not because of their tectorial membrane attachment, but because of fluid motion. Reprinted with permission from Dallos P, Ryan A. Physiology of the inner ear. In: Northern JL, ed. *Hearing Disorders*. Boston: Little, Brown: 1976: 95.

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Fig. 7-7. Transmission of sound waves through the cochlea. Reprinted with permission from Otologic diagnosis and treatment of deafness. *Clinical Symposia.* 1870;22(2):42. Slide 1163. West Caldwell, NJ: CIBA-GEIGY.

HEARING LOSS AND AUDITORY DAMAGE

The auditory system, although somewhat sheltered anatomically under the temporal bone at the base of the skull, is not immune to environmental hazards. Prolonged or intense exposure to noise can be detrimental to the auditory system.

Audiometric Threshold Shifts

Noise alters auditory structure and function and causes a subsequent loss of hearing sensitivity known generally as a noise-induced hearing loss. The effects may be temporary or permanent. Typically, an audiometric threshold (ie, the intensity, measured in dB HTL, at which a human can just detect a specific frequency) is measured both before and after an exposure to noise, and any measured difference in hearing sensitivity is referred to as a threshold shift. If the threshold measured after noise exposure recovers to its preexposure sensitivity, the loss is referred to as a noise-induced temporary threshold shift (TTS). If the postexposure sensitivity of the threshold does not fully recover to its preexposure level, the loss is referred to as a noise-induced permanent threshold shift (PTS).

For years, audiologists have known that a relationship exists between the audiometric frequency of noise and the resulting frequency of the maximum threshold shift. For high-intensity, pure-tone exposures, the greatest threshold shift is most often demonstrated at a frequency one-half to one octave (ie, one-half to one doubling of the observed frequency) above the frequency of the noise. For example, a noise at 2500 Hz would produce an audiometric shift at 4000 Hz. For broad-band noise with equal energy in all bandwidths, however, the maximum threshold shift occurs between 3000 and 6000 Hz. In mammals, this phenomenon is explained by both cochlear mechanics and the location and maximum amplitude of the vibration of the partition (ie, the basilar membrane and the organ of Corti). Cochlear partition vibration patterns do not increase linearly with the amplitude of the sound wave at all frequencies. As the sound-wave amplitude (the intensity of the noise) becomes greater, the vibration becomes less localized and moves toward the basal portion of the cochlea.[6] This vibration damages a locus of the cochlear partition that is more basal than the stimulating frequency, and causes a subsequent audiometric loss at a frequency higher than that of the insulting noise.

Influence of the Outer and Middle Ears on Hearing Loss

Although most discussions of noise-induced hearing loss focus on the damage that occurs in the inner ear, the outer and middle ears also play roles in noise-induced hearing loss.[7] The characteristics of the outer ear create frequency enhancement and those of the middle ear create frequency selectivity. These two mechanisms help to explain why noise-induced hearing loss is so often found at 3000 to 4000 Hz, which audiologists describe as a classic "notch" on the audiogram.

The resonant characteristics of the ear canal, which are determined by its length and volume, enhance frequency in the following way: at 2500 to 3500 Hz, which is the ear canal's resonant frequency, the sound-pressure level (dB SPL) (ie, the variation of air pressure due to a disturbance in the acoustic range) is increased at the eardrum by 15 to 20 dB compared to the dB SPL at the ear canal's entrance (Figure 7-8).[8] Thus, the resonance of the ear canal provides a high-frequency boost of energy that effectively changes the spectral components of any sound that enters it. Due to cochlear mechanics, an audiometric threshold loss occurs one-half to one octave above the frequency of the insulting noise; therefore, an energy boost at 2500 to 3500 Hz and a resulting threshold loss at 3000 to 6000 Hz is consistent with this principle.

By comparison, the middle ear inherently discriminates against certain frequencies. The transfer functions of the middle ear allow the mid- to high-frequency sounds (defined here as those between 1500 and 4000 Hz) to pass through it more efficiently than the low-frequency sounds, with the low-frequency sounds reaching the inner ear at a reduced intensity (relative to their intensity when they entered the ear canal). This allows sounds at frequencies greater than 1000 Hz to be transferred to the inner ear more easily. The physical alteration of sound before it reaches the inner ear is only partially responsible for different noise spectra that yield identical audiometric configurations, with hearing losses first measured at 3000 to 4000 Hz.

The middle ear contains two muscles, the stapedius and the tensor tympani, which contract reflexively in response to sound. Early theories on the functions of these muscles purported that this acoustic reflex protects the ear from loud sounds, because when the reflex occurs, the middle ear is stiffened and becomes a less

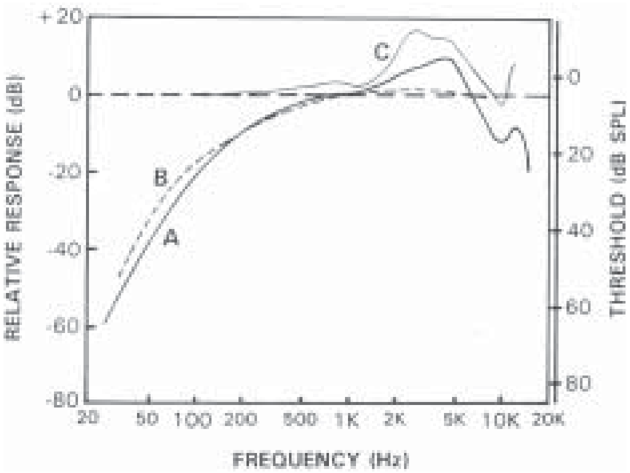

Fig. 7-8. Curve A: Response characteristics of the auditory system. A minimum audibility curve has been inverted as if a frequency-response curve had been "run" on the auditory system (actual thresholds, in dB SPL re 2 x 10^{-3} N/m^2, are shown on the right for reference). Curve B: A weighted response curve for sound-level measurement. Curve C: Sound pressure appearing at the eardrum as a function of the pressure in the sound field. Reprinted from Durrant JD. Anatomical and physiologic correlates of the effects of noise on hearing. In: Lipscomb DM, ed. *Noise and Audiology*. Baltimore: University Park Press; 1978 (out of print). Photograph: Courtesy of John D. Durrant, Philadelphia, Penn.

effective transmission system. Historically, this theory has been criticized for the following reasons:

- The reflex response fatigues rapidly, making it ineffective for continuous sounds.
- The muscle action is too slow (50–100 msec from latency to activation) for impulse sounds.
- The reflex provides protection only at frequencies below 1000 to 1500 Hz.
- The reduction of sound transmission is too small to have a protective effect.

The protective role of the muscles of the middle ear remains uncertain. Real-world stimuli, such as intermittent noise in a factory, may neutralize some of the above criticisms of reflex protection. For example, a noise may be of such short duration that the fatigue factor is rendered moot. Individual variability certainly exists in the degree of reflexive response. Numerous scientific papers discuss the relationship of the acoustic reflex to noise-induced hearing loss; promising new findings indicate that the role of the reflex in hearing may be more critical than was previously thought.[9–13]

Distinction Between Noise-Induced Hearing Loss and Acoustic Trauma

Current literature on damage to the cochlear structures is separated into distinct categories: noise-induced hearing loss and acoustic trauma. These categories may seem to be a contradiction in terms because acoustic trauma produces noise-induced hearing loss. However, an understanding of the anatomical consequences of the two shows that the types of injury are quite different.

Noise-induced hearing loss refers specifically to an injury that is caused by repeated exposures to moderate- or high-intensity noise. The noise may initially cause only a TTS, but at some point, the injury may become a PTS. This type of hearing loss, regardless of the frequency of the noise that caused it, usually begins audiometrically at 3000 to 6000 Hz and spreads to both higher and lower frequencies. The mode of destruction is more subtle, and the auditory effects evolve more slowly, than with acoustic trauma. Pathological changes may include (*a*) damage to intracellular structures and to the cilia of the receptor cells, (*b*) swelling of the nerve endings, (*c*) changes in vascular pathways, (*d*) biochemical changes in the cochlea, and (*e*) cell damage to the lateral wall of the cochlea in the stria vascularis and spiral ligament.

Damage to areas other than the receptor cells is usually found only when hair cell loss is almost complete. After the hair cells are injured, neural degeneration will appear. Some similar pathological injuries appear in both structures (Figures 7-9 through 7-12).

Much of the research on the auditory effects of noise has focused on the auditory periphery (ie, all the anatomical structures of the auditory system excluding the cerebral cortices and the brainstem). The central nervous system (CNS) response to noise insult—or to any type of damage in the auditory periphery—is still being investigated. Knowledge of the effects of hazardous noise on CNS function is expanding rapidly and new information on neural-feedback systems to the ear and how to protect it from acoustic overstimulation is forthcoming.

Acoustic trauma refers to injury that is caused by impulse or impact sounds of short duration and high intensity, which produce immediate, permanent hearing loss. The mode is mechanical. All structures of the ear are vulnerable to mechanical damage, but the most susceptible is the organ of Corti. Mechanical trauma to the auditory system usually consists of both PTS and TTS components, but some audiometric recovery (of the TTS component) may occur over a period of weeks. The audiometric frequency of the

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Fig. 7-9. This scanning-electron micrograph shows a pattern often seen in bent stereocilia of an outer hair cell (arrows) and in stereocilia after more severe damage from pure-tone stimulation. Patches of damage may extend over a full turn of the cochlea. Reprinted with permission from Hunter-Duvar IM, Suzuki M, Mount RJ. Anatomical changes in the organ of Corti after acoustic stimulation. In: Hamernik RP, Henderson D, Salvi R, eds. *New Perspectives on Noise-Induced Hearing Loss*. New York: Raven Press; 1982.

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Fig. 7-10. Scanning-electron micrograph of the cochlea at a 3,000-fold magnification about 15 mm from its base in a guinea pig exposed to impulse noise. Several outer hair cells in the third row are missing. Two hair cells (arrows) have missing hair bundles. Reprinted with permission from Nilsson P, Erlandson B, Hakanson H, Ivarsson A, Wersall J. Anatomical changes in the cochlea of the guinea pig following industrial exposure. In: Hamernik RP, Henderson D, Salvi R, eds. *New Perspectives on Noise-Induced Hearing Loss*. New York: Raven Press; 1982.

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Fig. 7-11. This scanning-electron micrograph shows an area of disrupted cilia of outer hair cells after acoustic stimulation. The proximity of the cells has allowed the cilia on adjacent cells to collide (arrows). Reprinted with permission from Hunter-Duvar IM, Suzuki M, Mount RJ. Anatomical changes in the organ of Corti after acoustic stimulation. In: Hamernik RP, Henderson D, Salvi R, eds. *New Perspectives on Noise-Induced Hearing Loss*. New York: Raven Press; 1982.

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Fig. 7-12. Scanning-electron micrograph of bent and fused stereocilia on inner hair cells. Reprinted with permission from Hunter-Duvar IM, Suzuki M, Mount RJ. Anatomical changes in the organ of Corti after acoustic stimulation. In: Hamernik RP, Henderson D, Salvi R, eds. *New Perspectives on Noise-Induced Hearing Loss*. New York: Raven Press; 1982.

hearing loss may vary among individuals. Weapons fire may cause an asymmetrical high-frequency hearing loss that is due to the protective "head shadow effect" (ie, protection afforded the right ear by the shooter's own head and shoulder). For example, the hearing loss would be worse in the left ear for right-handed shooters. An asymmetrical hearing loss is also not unusual after exposure to the noise of an explosion. There is a greater chance that the audiometric configuration after this type of injury may be flatter; the pressure wave from an explosion may also damage the middle ear and add a low-frequency component to the hearing loss.

MECHANISMS OF AUDITORY INJURY

The major mechanisms of auditory injury are mechanical and metabolic. Vascular injury may also occur following noise exposure, but a specific injury mechanism has not yet been determined.

Mechanical damage, in which noise overstimulation directly injures cochlear structures, is caused by intense noise of rapid onset and short duration and its consequent acoustic trauma. Excessive force on the cochlear partition creates excessive stresses and displacement, which tear and disrupt the cochlear structure. Mechanical damage can include

- injuring hair cells in the organ of Corti;
- tearing the entire organ of Corti away from the basilar membrane so that it floats within the scala media[14,15];
- rupturing the basilar membrane[16];
- rupturing the Reissner membrane, which allows endolymph and perilymph to mix, creating a biochemical environment that is toxic to the receptor cells[16];
- tearing holes in the reticular lamina, allowing endolymph to flow into the organ of Corti[17];
- ripping apart tight cell junctions; and
- swelling and degeneration of hair cells, nerve fibers, and nerve endings in the organ of Corti at the apical and basal edges of the lesion.[18]

Data from researchers who exposed chinchillas to blasts demonstrate great variability in both sensory cell loss and in the formation of scar tissue.[14] This scar tissue prevents mixing of the cochlear fluids, and therefore prevents additional sensory cell loss.

Metabolic injury is manifested by disruption of internal cell processes. Rather than the intense mechanical force associated with impulse noise, this type of damage is more often associated with slow, insidious, noise-induced hearing loss. However, metabolic damage also occurs after direct mechanical damage from exposure to impulse noise.[19] Characteristics of metabolic damage include

- injury to hair cells and afferent dendrites;
- degeneration of scattered sensory cells, as a result of daily exposure, with damage more likely to affect outer rather than inner hair cells; and
- an increase in the number of damaged sensory cells with increasing noise exposure.

One theory attributed hair cell damage to exhaustion of cytochemical or enzymatic materials after or during exposure to noise.[20] This physiochemical theory is known as the metabolic exhaustion theory.[21] Numerous reports cite the apparent relationship between auditory damage and metabolic exhaustion. Morphological changes in hair cell structures (specifically, of mitochondria and of the endoplasmic reticular system) suggest that deficits occur in fuel utilization, in protein synthesis, and in energy production.[1] These metabolic or homeostatic disruptions, whether they occur independently or collectively, are considered to result from exposure to excessive noise: enzyme systems that are critical to these processes are found in noise-damaged cellular structures.[1] Cellular degeneration follows severe insults of this type.

The metabolic theory of damage has become even more pertinent because new information changed our view of the cochlea's role in auditory transduction.[22] Previously, the cochlea was thought to be a passive analyzer and transducer of sound. We now understand that the cochlea has its own motile properties and participates in an active transduction process that requires energy to change hair cell and stereocilia mechanical properties in response to sound. Because the hair cells are involved actively in sound transduction and analysis, the metabolic theory of damage may have greater responsibility for the injury process than was previously thought.

The auditory system has two independent vascular supplies: first, a dense capillary network, the stria vascularis, which lines the outer wall of the scala media, and second, radiating arterioles that serve the organ of Corti. The stria vascularis influences chemical and oxygen balances to maintain endolymphatic metabolism, while the radiating arterioles provide oxygen to the organ of Corti (Figure 7-13).

Regional vascular abnormalities have been found after exposure to excessive noise. The vascular theory

Fig. 7-13. Vascular network of the rat cochlea. This is a low-magnification, scanning-electron photomicrograph of tissue prepared by injecting latex into the vascular system. After the latex solidified, all the cochlear tissue was dissolved in acid to reveal only latex-filled vascular channels. Photomicrograph: Courtesy of Jack A. Vernon, PhD, Kresge Hearing Research Laboratory, University of Oregon, Portland, Ore.

asserts that changes in the vascular system occur after exposure to noise and the resultant less-efficient delivery of nutrients to, and expulsion of waste products from, the cochlea make the auditory system more susceptible to injury. This may occur in conjunction with either metabolic or mechanical damage (Figures 7-14 and 7-15). Many vascular variables have been studied (Figure 7-16), including the number and the density of erythrocytes, the diameter of the blood-vessel lumens, the frequency and size of the perivascular cells, changes in oxygen tension, the thickness of the blood-vessel walls, and edema and atrophy of the stria.

The role of vascular factors in noise-induced hearing loss has been discussed for years.[1,15,23–27] However, no consensus on the type and degree of vascular changes, the ultimate effect of the change on the cochlea, or the underlying mechanism responsible for the change has been reached. Conflicting results—due to the many different variables measured and the methodologies and species of test animals used—make conclusions difficult. Vascular abnormalities that occur in response to excessive auditory stimuli are probably one contributing variable of the metabolic theory.

One study utilized carbogen to investigate the relationship between noise and vascular deficits.[28–30]

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Fig. 7-14. Capillary vasoconstriction at the second turn of the cochlea with endothelial cell swelling and trapped erythrocytes (arrows) in inner and outer spiral vessels. Noise exposure was 118 to 120 dB for 30 hours continuously. Reprinted with permission from Hawkins JE Jr. The role of vasoconstriction in noise-induced hearing loss. *Ann Otol Rhinol Laryngol.* 1971;80:903–913.

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Fig. 7-15. A transmission-electron micrograph of a trapped erythrocyte in an outer spiral vessel at the third turn of the cochlea. The lumen is reduced to 1 micron (μ) or less. Noise exposure totaled 118 to 120 dB for 110 hours. Reprinted with permission from Hawkins JE Jr. The role of vasoconstriction in noise-induced hearing loss. *Ann Otol Rhinol Laryngol.* 1971;80:903–913.

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Fig. 7-16. Schematic representation of a cochlear vessel in which subjectively evaluated vascular parameters are depicted. Reprinted with permission from Axelsson A, Vertes D. Histological findings in cochlea vessels after noise. In: Hamernik RP, Henderson D, Salvi R, eds. *New Perspectives on Noise-Induced Hearing Loss*. New York: Raven Press; 1982.

Carbogen (95% oxygen and 5% carbon dioxide), rich in oxygen compared to ambient air, was inhaled in different experimental noise-exposure paradigms that utilized both humans and chinchillas as subjects. The assumption was that increasing the oxygen available to the cochlea would (*a*) offset the detrimental effects of the vascular changes and (*b*) render the cochlear structures less susceptible to the hazards of noise. Both post- and prestimulatory carbogen inhalation decreased TTS, increased recovery rate, and, in chinchillas, decreased sensory cell damage. These results were considered preliminary, although apparently little follow-up research has been conducted in this area.

Another study tested the drug Dextran-40, but the evidence, although promising, was inconclusive.[31] During the 1970s, the West German army used Dextran-40 to treat military personnel who had sustained acoustic trauma. Dextran-40 supposedly increased circulation to the cochlea, and thus was assumed to facilitate the recovery process. While the reported results indicated that the treatment was effective, the experimental design—the selection of subjects and the lack of appropriate controls—limited the application of the results.[31]

Inner and Outer Hair Cell Loss

The inner and outer hair cells are morphologically and functionally different classes of cells. The two cell types differ in their size, shape, cochlear organization, cell-support system, stereocilia pattern, resting potential, and neural-innervation pattern. Their respective roles in audition are still being studied, refined, and changed.

Early cochlear dissection techniques provided information on hair cell counts, such as the number of inner hair cells compared to the number of outer hair cells that remained after exposure to noise. Today we are capable of more extensively analyzing cochlear hair cells for their qualitative morphological changes as well as for quantitative changes after exposure to noise. For example, simply counting the hair cells that remain after exposure to noise is not conclusive because myriad pathologies may exist in the remaining hair cells.

It is still generally true that, following exposure to high-intensity noise, outer hair cell loss occurs before inner hair cell loss. While outer hair cells are more susceptible to damage from noise, losing inner hair cells causes much greater hearing loss than does losing an equal number of outer hair cells. Data from experiments with chinchillas show that exposures to impulse noise may produce lesions with massive outer hair cell loss over 80% of the cochlea, but hearing sensitivity losses in the same animals seldom exceed 40 dB.[14] The data also show that, with lesions localized to the middle of the cochlea, hearing thresholds may be near normal if outer hair cell loss does not exceed 10% to 30%.[14] In both instances, researchers found that the inner hair cells appeared quite normal.

Much of the susceptibility of the outer hair cells can be explained by two mechanical factors: first, the outer hair cells undergo greater displacement due to their location on the basilar membrane, and second, the tips of the stereocilia of the outer hair cells are embedded in the undersurface of the tectorial membrane, which allows more direct, mechanical movement and consequent stress. In contrast, the cilia of the inner hair cells are not embedded in the tectorial membrane, and their movement occurs not from mechanical linkage but from eddy current through the endolymph.

An additional factor that may play a role in this susceptibility is the pattern of neural innervation. The outer hair cells are innervated directly by efferent neural fibers. Although the role of the efferent fibers is still being studied, without them, the susceptibility of the outer hair cells may be even greater.

Outer hair cells are also known to be more susceptible to ototoxic drugs than are inner hair cells , so the outer hair cells' increased susceptibility to noise is probably due to more than just mechanical or neural factors. Specific metabolic processes of outer hair cells that differentiate them from inner hair cells appear to be partially, if not entirely, responsible, but these metabolic processes have yet to be delineated.

Stereocilia and Rootlet Damage

After the composition and structure of stereocilia were identified, researchers investigated morphological changes in stereocilia that followed exposure to noise.[32–35] Hair cell stereocilia are actin filaments, with crossbridges between filaments providing rigidity to the stereocilia. The movement of the stereocilia causes ion flow across the hair cell membrane and a subsequent voltage change: this is thought to initiate the release of the neurotransmitter substance. The stereocilia are very vulnerable to trauma from noise and may represent the weak link in the process of auditory transduction. Electron-microscopic studies suggest that the rootlet structures, which anchor the cilia within the hair cell, are particularly susceptible to noise.

When PTS and stereocilia damage are correlated, most PTS can be directly linked to stereocilia damage. Following acoustic injury, subcellular stereocilia pathology can be found on hair cells that otherwise appear to be normal.[36] Permanent damage to stereocilia is documented in numerous studies and includes disarray, fusion, loss of the bundle, scarring of the bundles, and the appearance of floppy, giant, elongated stereocilia.

Temporary and Permanent Threshold Shifts

Noise can affect hearing either temporarily or permanently. Repeated TTS will presumably lead to PTS, although this presumption assumes that individual susceptibility to TTS and PTS are similar. Evidence from controlled laboratory experiments that demonstrate this relationship has not yet been acquired, although the hypothesis appears logical.

TTS studies are important in assessing noise hazards. Damage-risk criteria specify noise-exposure limits and their consequent associated risks. These criteria are based predominantly on animal experimentation in which damage, possibly TTS, occurred over a period of days to weeks. Real-world noise exposures experienced by humans in their workplaces, can last for 40 or more years and produce PTS. In the damage-risk criteria process, TTS measures are utilized and those results are extrapolated to PTS. Three postulates relating TTS and PTS were developed for the purposes of defining damage-risk criteria:

1. TTS 2 minutes after exposure is a consistent measure of the effects of a single day's noise exposure.
2. All exposures that produce a given TTS 2 minutes after exposure are equally hazardous.
3. TTS 2 minutes after 1 day's exposure is approximately equal to PTS after 10 or more years' exposure.[37]

The correlation of TTS and PTS continues to concern researchers in auditory science. The time constraints of following the course of human hearing over a 25- to 40-year history of occupational noise exposure seems to ensure that studies on animals and TTS measurements will continue as methods of auditory research into the next century.

New information is providing some insight into the physiological relationships and differences between PTS and TTS. The biological bases of PTS are relatively well defined—stereocilia damage with changes in rootlet structure and hair cell bodies—and pathological conditions of stereocilia probably account for most PTS.[38] Quite simply, if there is no transduction process at the level of the sensory cell itself, there will be no response to auditory stimuli.

However, the biological bases of reversible TTS are subtle indeed[36] and many factors may be responsible. Several studies suggest that rootlet damage to stereocilia may change cochlear micromechanics and be responsible for TTS. Subtle changes in the stereocilia that may be transient in nature, such as initial stiffness or disarray of the stereocilia, are also under investigation. Some potentially reversible factors include vascular changes, metabolic exhaustion, and chemical changes in the hair cells.

Correlation Between the Audiogram and Histological Damage

An audiogram does not accurately predict either cochlear pathology or the integrity of the inner ear. Health professionals who are responsible for identifying noise-induced hearing loss rely on the audiogram for determining cochlear damage, but they generally do not understand that the audiometric configuration does not completely reflect the cellular condition of the cochlea. There may be considerable cochlear damage in the apical region, with normal hearing registered in the low-frequency portion of an audiogram.[14,39,40] In fact, it is probably impossible to predict the complex pattern of cochlear pathology from an audiogram.[41] The fact that a patient can hear does not mean that the cochlea is not damaged. An audiogram will provide the physician with a complete picture of a person's hearing as measured by an audiometer, but physicians should not make the intuitive leap and assume that there is no cochlear pathology.

SUSCEPTIBILITY TO NOISE-INDUCED HEARING LOSS

For years, researchers have been interested in the many individual differences in susceptibility to noise-induced hearing loss. Demographic studies show a 50-to-60 dB variability in hearing threshold shifts among individuals with an identical history of industrial noise exposure.[42,43] While demographic studies are limited in their reconstruction of individuals' complete auditory histories, the variation in susceptibility to noise-induced hearing loss is nonetheless astounding. A number of anatomical factors may contribute to this variability, such as qualities of tympanic membranes, individual differences in the contours of ear canals, middle ear characteristics, and the sensitivity of the muscles of the middle ear. However, these factors alone do not account for the magnitude of variability.

Until this variability is well understood, our ability to identify damage-risk criteria will remain inexact. A combination of several factors probably determines susceptibility to auditory damage, although each factor's relative influence is as yet undefined. A clinical battery of auditory tests or a mathematical or statistical model that incorporates the predictive effects of each factor may ultimately be developed.

The military would greatly benefit if those soldiers who are at risk for noise-induced hearing loss could be identified. Identifying and following the soldiers who are susceptible could save money by eliminating the need to retrain them for other jobs. Awareness of a predisposition to noise-induced hearing loss could also influence early counseling on career choices.[44] Soldiers with a high susceptibility require an emphasis on auditory management, a more frequent review of hearing acuity, and more intensive training in the care and use of hearing protectors.

Stimuli Variables

Noise-induced hearing loss may be affected by the following stimuli variables: (*a*) combinations of continuous and impulse noise, (*b*) intermittent noise (ie, noise that has a rest time), and (*c*) exposure frequency (in Hz).

Combinations of Continuous and Impulse Noise

Demographic studies indicate that the development of hearing loss may be accelerated when individuals are exposed to noise environments that contain both continuous and impulse noise, compared with exposure to continuous noise alone.[19] These demographic studies support data from controlled laboratory experiments. Workers exposed to impact and continuous noise also show extreme variability in the incidence of PTS.[19] The literature supports an interaction between continuous and impulse noise under specific conditions: when impulse levels are greater than 147 dB SPL, and when the two noise types overlap both spectrally and temporally.[45] This has particular importance to armored divisions, which are often exposed to continuous- and impulse-noise combinations.

Intermittent Noise

For the same total energy transmitted, intermittent noise is thought to produce less hearing loss than continuous noise. Researchers experimenting with chinchillas found that intermittent exposures to noise produce less temporary and permanent hearing loss and less cochlear damage than continuous exposure to noise of an equal energy. Two variables, which they found must be considered with intermittent noise, are (1) recovery during the noise off-time (quiet time) and (2) reduced adaptation of the acoustic reflex.[46] Recently, another investigator reported that intermittent exposures appear to make the ear more resistive to noise injury; exposure to low-intensity noise for several days may reduce the amount of PTS from exposure to a higher-intensity noise.[47] The scientific world awaits further developments regarding this new information.

Exposure Frequency

Generally, for noise exposure of a moderate intensity, high-frequency sound damages a restricted area of the basal region of the cochlea, and low-frequency sound damages both basal and apical areas of the cochlea. In experiments with chinchillas, researchers have analyzed cochlear damage related to (*a*) continuous exposure to low-frequency noise, (*b*) continuous exposure to high-frequency noise, and (*c*) interrupted noise exposures.[17,48–50] High-frequency (in this instance, a range of frequencies with a center frequency of 4000 Hz), moderate-intensity noise caused damage in the region of the organ of Corti that is basal to the frequency location of the basilar membrane that was tuned to that exposure. As the intensity increased, damage spread both basally and apically. Low-frequency (a range of frequencies with a center frequency of 500 Hz), moderate-intensity noise caused damage predominantly to the outer hair cells in a broad area of the low-frequency region. As duration and intensity of the noise increased, the damage included more outer hair cells, with additional lesions in the high-frequency basal portion of the cochlea. The damage was more severe in the basal area than in the apex, and was also more severe than the damage caused by the high-frequency exposures. The loss of inner hair cells did not begin to occur until many outer hair cells were damaged. (From 30% to 50% of the outer hair cells may be missing in the apical region of the cochlea before the low-frequency thresholds are affected.) Interestingly, when interrupted low-frequency noise was presented to the chinchillas (6 h of noise with 18 h of rest), damage in the low-frequency region of the cochlea was reduced significantly. No such protective effect was found for loss in the high-frequency region. This relationship is consistent with the 4000-Hz notch that first appears on an audiogram from noise-induced hearing loss, regardless of the frequency of the insulting noise.

Variables That Affect Susceptibility

Factors that affect susceptibility to noise-induced hearing loss are (*a*) ototoxic drugs, (*b*) physical characteristics, (*c*) previous noise-induced hearing loss, (*d*) vibration, and (*e*) other variables.

Ototoxic Drugs

The aminoglycoside antibiotics streptomycin and neomycin produce more auditory sensory damage when combined with noise than they do when they are administered without noise.[41,45,51] Aminoglycoside therapy may destroy sensory hair cells and the stria vascularis of the cochlea, although the magnitude of the interaction between noise and the drugs appears to depend both on the intensity of the noise and the dosage of the drug. Thus, a patient receiving aminoglycosides should be considered to be at increased risk of a threshold shift when he or she is exposed to loud noise.

Cisplatin, a drug used in the treatment of some cancers, can also significantly increase auditory damage from noise. Again, the magnitude of the interaction depends on the intensity of the noise. Studies with animals show high concentrations of cisplatin in the stria vascularis and identify this area as the site of the pathophysiology.[41]

Salicylates, which are associated with temporary hearing loss and tinnitus, have also been implicated in causing an increase of TTS when taken in conjunction with noise exposure. However, salicylates have not shown an increase in PTS with noise exposure.[51] The debate over possible synergy between salicylates and noise continues.

Physical Characteristics

Physical characteristics that have been studied relative to noise-induced hearing damage are (*a*) melanin content, (*b*) age, and (*c*) serum magnesium levels. Melanin is present in the inner ear and is assumed to be involved in the normal function of the auditory system, although its exact role is undefined. Furthermore, the relationship of the melanin content in the iris or the skin to the melanin content in the ear has not yet been established. Several studies have investigated the relationship of melanin to noise-induced hearing loss, and assert that individuals with less melanin in their irises (those with blue or green eyes) exhibit more noise-induced hearing loss than those with brown eyes. Similarly, retrospective studies of black and white industrial coworkers have suggested that black workers experience less hearing loss than white workers. But the differences may not be industry related and there appears to be little evidence that eye color or skin pigmentation can accurately predict an individual's susceptibility to noise-induced hearing loss.[45]

Unlike the tenuous relationship of melanin to noise-induced hearing loss, however, strong support exists for age-dependent changes in susceptibility. Evidence from studies with animals indicates that once the auditory periphery is fully developed, the younger the animal, the greater the damage from noise exposure.[45] Studies on mice show that the greatest hearing loss for younger animals occurs only at the higher-intensity exposures.[52] We assume that the hearing losses from noise exposure and age (presbycusis) combine; this is the basis for using age-corrected hearing thresholds in compensation cases.

Similarly, studies with animals suggest a relationship between serum magnesium levels and differences in the susceptibility to noise-induced hearing loss. Magnesium is present in perilymph, and a deficiency in magnesium has been linked to energy depletion and irreversible damage to the hair cells.[53,54]

Previous Noise-Induced Hearing Loss

People who have a history of previous noise-induced hearing loss appear to have unchanged susceptibility to additional noise-induced hearing loss. Generally, one can expect to find less TTS as preexposure hearing threshold level increases. Literature on this subject concludes that (*a*) when the region of the basilar membrane that was injured by prior noise exposure coincides with the region that is affected by current noise exposure, the threshold shift is less in the impaired ear, but the resultant shifted thresholds are identical, and (*b*) when the region of the basilar membrane that was injured by prior noise does not coincide with the region that is affected by the current noise exposure, the total region of damage is the simple sum of the two.[45]

Vibration and Other Variables

Vibration has a small, consistent, minor effect on the sensitivity of human hearing.[41] Although researchers have found evidence of a relationship between noise and whole-body vibration, the degree of interaction appears small.[45] A recent investigation of noise and vibration interaction in chinchillas demonstrated relatively small and inconsistent effects on hearing and sensory cell populations. The researchers concluded that "an increased risk of noise-induced hearing loss from vibrations in the industrial population is probably relatively small."[55]

The preceding variables are in no way inclusive of all affecting agents. For example, gender, hormonal cycles and oral contraceptive use,[56,57] levels of carbon monoxide,[51] air temperature, and cigarette smoking[58] have all been investigated regarding their interaction with noise-induced threshold shifts. The psychological role of noise as a stressor and the alteration of the physiological processes mediated by the autonomic, central nervous, and endocrine systems have been reviewed.[59] The general theme of research in this area is the interaction of noise with conditions that result in peripheral vasoconstriction, an elevated heart rate, and increased blood pressure.[59]

Future Research Objectives

Much of the literature on the physiological effects of noise consists of data obtained from animals during relatively short exposures (days or weeks). Studies paralleling the damage to hearing that accumulates over a worker's lifetime in the real world are needed and should address

- models to predict hearing loss based on cellular damage relative to exposure characteristics[60];
- greater study of exposure to low-intensity noise emphasizing metabolic damage because many studies report on high-intensity exposures and emphasize mechanical damage;
- systematic descriptions that trace the physiological pathways of cellular injury and cellular degeneration quantitatively, to improve our understanding of the mechanisms that cause the anatomical change[1];
- determination of critical levels for damage from various types of noise;
- further refinement of the relationship between TTS and PTS and their accompanying anatomical correlates; and
- further investigation of interactive agents and environmental stressors that can affect noise-induced hearing loss.

HEARING IMPAIRMENT IN THE U.S. ARMY

Noise-induced hearing loss is one of the most prevalent occupational health impairments in the army. The magnitude of the problem can be estimated from the following sources: (*a*) a hearing-loss prevalence study conducted in 1975, (*b*) hearing-loss data from the U.S. Army's Hearing Evaluation Automated Registry System (HEARS), and (*c*) compensation expenditures.

The Hearing-Loss Prevalence Study

In 1975, audiometric data were obtained from 3,000 enlisted men representing three combat branches (infantry, armor, and artillery) and five time-in-service categories.[3] In this prevalence study, significant hearing loss was defined as that decrement in hearing that enabled a soldier to qualify for an H-2 profile or worse. A detailed discussion of the hearing-profile system is beyond the scope of this chapter; however, the severity of hearing loss that a soldier must exhibit to obtain an H-2 profile can be illustrated: the upper limit of an H-1 profile defines the hearing sensitivity of a 70-year-old man.

This prevalence study produced the following salient findings:

- Approximately 20% to 30% of all combat-arms personnel with more than 1.5 years of service had significant hearing losses.
- Over 50% of combat-arms personnel with more than 15 years of service (the army's senior noncommissioned officers) had significant hearing losses.
- The prevalence of hearing loss was roughly the same in all three combat-arms branches.
- A substantial difference existed between the prevalence of hearing loss according to time-in-service, and this difference could not be explained on the basis of age.
- Most soldiers did not carry the appropriate profile for hearing; for example, the calculated profile from their last hearing test was different from the profile assigned to them.[3]

An update of this prevalence study is long overdue. After validation studies for threshold determination and more extensive analysis of personnel databases have been done, HEARS data will be used to reexamine hearing-loss prevalence in the army.

The Hearing Evaluation Automated Registry System

Approximately 500,000 Department of the Army (DA) military and civilian personnel are reported to be exposed routinely to hazardous noise.[61] From 1980 to 1990, almost 2 million audiometric evaluations of these individuals were accumulated in a mainframe database at Fort Detrick, Maryland. However, poor participation in HEARS has limited the value of the data that demonstrate its effectiveness. Figure 7-17 compares participation in the registry as a function of rank for enlisted personnel, and Figure 7-18 compares the prevalence of hearing loss by rank. Similar patterns exist for commissioned officers and warrant officers. By 1989, only 41% of all active-duty personnel were enrolled in HEARS. Even with this limited participation, the data indicate a high prevalence of hearing loss among military personnel. For example, 10% of all active-duty warrant officers and 6% of all enlisted and officer personnel in HEARS have an H-3 or worse hearing profile. This H-3 profile signifies a substantial hearing loss, for which some soldiers may require both a hearing aid and reclassification from a noise-hazardous occupation. If all of these individuals were reassigned to jobs that were free of noise hazards, the disruptions in work schedules and increased training costs would be substantial. Although data on training costs are calculated on a case-by-case basis and are not readily available through medical channels, high costs would be incurred by training personnel for entry into the noise-hazardous specialty, retraining personnel for reassignment to a noise-free job specialty, and training the replacement personnel in the original noise-hazardous specialty.[61]

The prevalence of hearing loss among civilians is calculated in HEARS under the Department of Labor (DOL) hearing-loss formula in terms of the percentage of hearing loss and potential monetary compensation. Of the 82,716 civilians in HEARS, 13,449 (16%) have potentially compensable hearing levels, as calculated from the results of their last hearing test.[61] Currently, the army's potential compensation liability would total approximately $93 million if all 13,449 individuals filed and were found to be compensable.[61]

Compensation Expenditures

Although the figures do not reflect the more important factors—decreased quality of life and decreased job performance—that are associated with communication handicaps from hearing loss, the DoD's compensation expenditures have been staggering (Figure 7-19).[61] In 1990, the army was credited for 39,271 of the total 62,012 cases of primary hearing-loss disability (ie, when hearing loss is the greatest or only disability) and for 91,443 of the 171,192 secondary disabilities (ie, when hearing loss is one of several compensable disabilities) (Figure 7-20).[61] But two additional points must be noted: (1) there are undetermined expenditures for other disabilities computed into the primary hearing-loss figures, and (2) these expenditures are funded through a separate Veterans Administration (VA) budget to which DoD agencies are not accountable.

In February 1987, the DOL, which administers workers compensation for all civilian federal employees, adopted the hearing-impairment formula of the American Academy of Otolaryngology. The new formula added 500 Hz to the frequencies 1000 Hz, 2000 Hz, and 3000 Hz that were already in use. Since 500 Hz is a frequency that is less affected by noise, the use of this

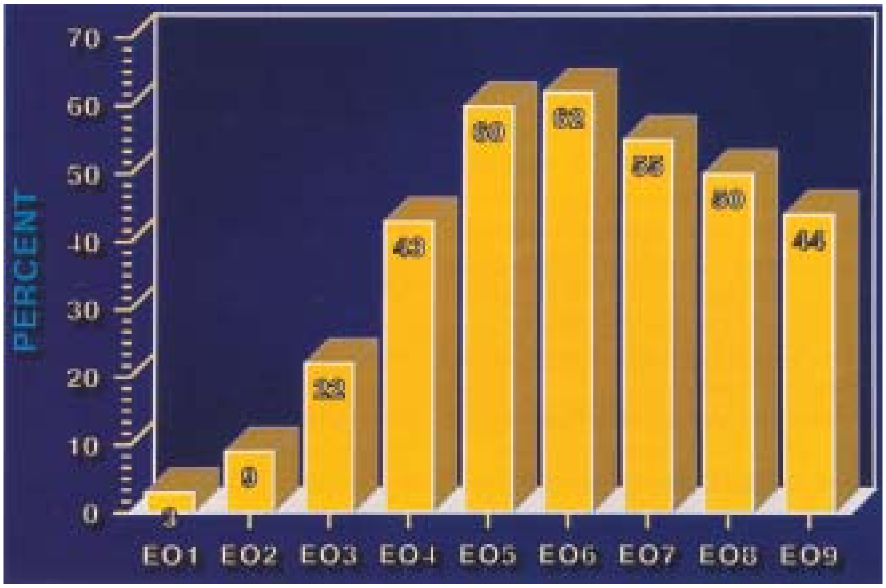

Fig. 7-17. Percentages of enlisted soldiers with a reference audiogram as a function of rank. An untimely reference audiogram and lack of subsequent audiometric monitoring precludes early detection of hearing loss. Source: Donahue AM. *Hearing Conservation Data Profile*. Aberdeen Proving Ground, Md: US Army Environmental Hygiene Agency; 1991. Armywide database 51-34-0251-91.

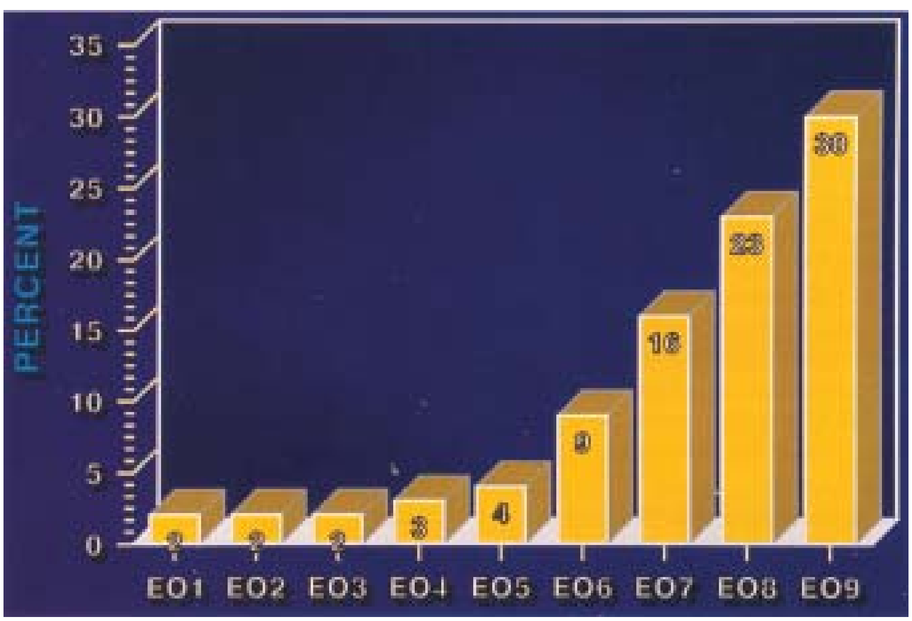

Fig. 7-18. Percentage of enlisted soldiers with a hearing profile worse than H-2 as a function of rank. The prevalence of hearing loss increases with rank and presumably with time in service. These increases are not attributable to aging. Source: Donahue AM. *Hearing Conservation Data Profile*. Aberdeen Proving Ground, Md: US Army Environmental Hygiene Agency; 1991. Armywide database 51-34-0251-91.

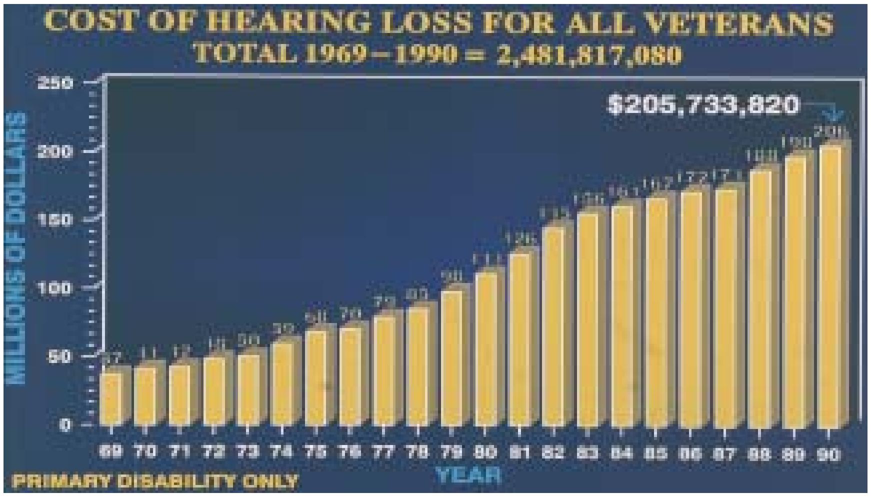

Fig. 7-19. Expenditures over the last 22 years for veterans in all services receiving hearing-loss compensation who had hearing loss as their primary disability. In the calendar year 1990, the army accounted for 67% ($138,138,804) of total primary-disability expenditures ($205,733,820). The total cost ($2,481,817,080) for 1969 to 1990 does not include expenditures for secondary-disability cases of hearing loss. Source: Donahue AM. *Hearing Conservation Data Profile*. Aberdeen Proving Ground, Md: US Army Environmental Hygiene Agency; 1991. Armywide database 51-34-0251-91.

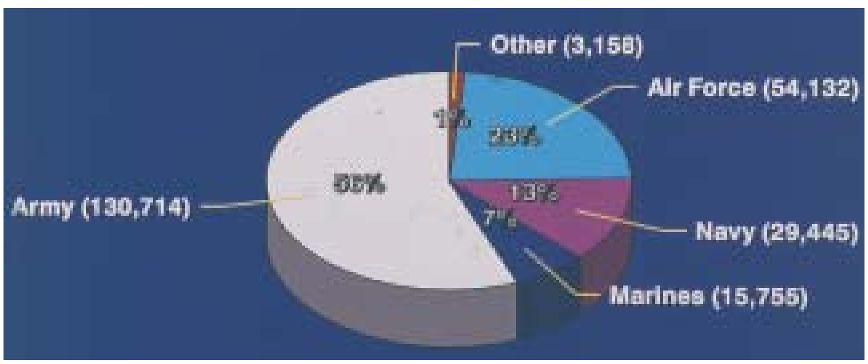

Fig. 7-20. The distribution of hearing-loss disability cases (primary and secondary) among the services. Veterans are included for calendar year 1990 only. Source: Donahue AM. *Hearing Conservation Data Profile*. Aberdeen Proving Ground, Md: US Army Environmental Hygiene Agency; 1991. Armywide database 51-34-0251-91.

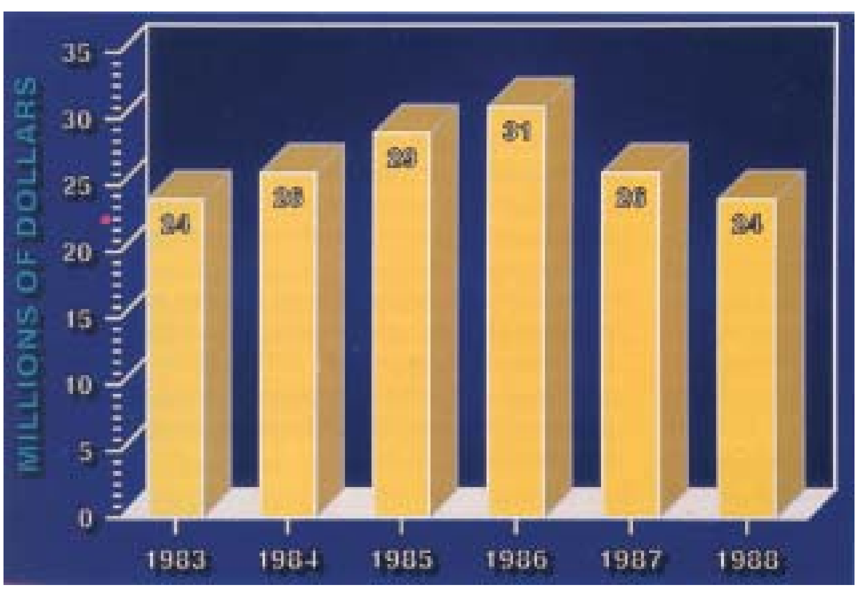

Fig. 7-21. Expenditures for civilian hearing-loss compensation for all federal agencies for fiscal years 1983 to 1988. Source: Donahue AM. *Hearing Conservation Data Profile*. Aberdeen Proving Ground, Md: US Army Environmental Hygiene Agency; 1991. Armywide database 51-34-0251-91.

formula reduced the number of awarded compensation claims for that year (Figure 7-21).

The latest data available from fiscal year 1990 show that the hearing-loss bill for all government agencies totaled $27,451,585, which constitutes 2% of the total monies paid for all forms of compensation ($1,440,980,764). The army was charged for 23% ($6,360,205) of the total hearing-loss bill, and accounted for 17% (908) of the 5,375 cases adjudicated. On average, the rate of hearing loss in the army was twice as high as the rate in the total federal government (4% versus 2%).[61] Moreover, since all civilian compensation is a charge back to the original agency, there is concern for reducing compensation at the DA level, where, in turn, charge backs are being directed down to the major command level and, eventually, to the installation. Current data portray a problem of sizable proportions; nevertheless, organizational accountability is linked to an accurate definition of this problem.

HEARING CONSERVATION IN THE U.S. ARMY

Noise-induced hearing loss is not a recent phenomenon in the army, nor are efforts to prevent it. Although it may seem to be contradictory, noise-induced hearing loss and measures to prevent it have coexisted for almost five decades. As the magnitude of this problem indicates, the army's efforts to prevent noise-induced hearing loss have not been entirely successful.

The development of military hearing conservation programs has been linked to the evolution of specialties in the fields of audition, speech science, psychoacoustics, and bioacoustics.[62] Milestones for army hearing conservation programs can also be linked to the establishment of facilities and the publication of key hearing conservation documents.

Facilities

Early army initiatives can be traced back to December 1941, when a research facility at Fort Knox, Kentucky, was established. Topics of investigation included the effects of noise on personnel efficiency, the nature of the temporary deafness that was caused by tank noise, and the physiological adaptation to tank noise. In August 1944 , a project that addressed these topics recommended that gun crews, gunnery instructors, and other personnel who were exposed regularly to gunfire blasts be provided with hearing-protective devices.[63] The army procured a single-flange earplug, the V-51R, for general issue to those who required protection.

In 1942, the forerunner of the U.S. Army Environmental Hygiene Agency (USAEHA), the Industrial Hygiene Agency, was established at The Johns Hopkins University. For the next 27 years, hearing conservation was largely an industrial hygiene function, both within this agency and in the field, with an emphasis on the identification of noise hazards. In 1969, a military audiologist was assigned to the USAEHA, which was then located at Edgewood Arsenal, Maryland. In that same year, the Bio-Acoustics Division was created at the agency with the mission to provide consultation and advice in the medical, engineering, and administrative aspects of hearing conservation.

While the Bio-Acoustics Division was concerned with studying operational noise problems and monitoring the effectiveness of the Hearing Conservation Program, other laboratories were established, including the U.S. Army Audiology and Speech Center at Walter Reed Army Medical Center, Washington, D.C.; the U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama; and the Human Engineering Laboratory, Aberdeen Proving Ground, Maryland. These laboratories were established to investigate noise-related problems involving protective equipment design, hearing loss, hearing protection, aural detectability, performance decrements caused by hearing loss, and aural rehabilitation.

Military Audiology and Other Disciplines

The specialty of audiology emerged from aural-rehabilitation centers that were established after World War II. By the late 1960s, there were 11 audiologists on active duty.[64,65] Today, more than 65 officers serve dual roles as clinical audiologists assigned to army hospitals or other medical installations or activities, and hearing-conservation officers who assist the local preventive medicine officer. They have the general responsibilities of monitoring and implementing the local Hearing Conservation Program. In this role, the audiologist is the responsible action officer for hearing conservation.

Because it is impossible for any one action officer to perform all hearing-conservation functions, the army employs a team approach. Although the disposition of resources is at the discretion of local commanders, program responsibilities for other related disciplines have evolved:

- Industrial hygienists have the primary responsibility for noise-hazard evaluation, and work

closely with facilities engineers to design and retrofit engineering noise controls.
- Occupational health nurses perform medical procedures such as fitting earplugs and providing audiometric testing for the civilian population, and manage programs in the absence of audiologists.
- Safety personnel perform a vital role in posting areas and equipment and enforcing the use of hearing protectors.
- Occupational health physicians have the final word in medical decisions and recommendations.
- Physician assistants, military corpsmen, civilian health technicians, and others also assist in accomplishing Hearing Conservation Program responsibilities.

Key Documents

Noise standards (ie, requirements for program implementation by the federal government) and documents that implement hearing conservation programs represent significant milestones in the development of these programs. The first document with standards was U.S. Air Force Regulation 160-3, which was issued in 1956.[66,67] For the next 25 years, the air force maintained the most well-established hearing conservation program in the military.

The army issued an implementing document in 1956 and revised it in 1965 and 1972.[68–70] However, the U.S. Army's Technical Bulletin, *Noise and Conservation of Hearing*, known as TB MED 251, did not include the Hearing Conservation Program requirements, but only recommendations for its implementation. The requirements for a program were outlined in a basic preventive medicine regulation, U.S. Army Regulation (AR) 40-5, which referred to the technical bulletin.[71] Unfortunately, because only a program outline was required by the regulation, only an outline existed. In 1977, the General Accounting Office (GAO) recommended that the DoD adopt a uniform policy on noise exposure.[72] A year later, a DoD Instruction (DoDI) was published to provide standards as well as uniformity to military hearing conservation programs.[73] The army's implementing document to the DoDI—TB MED 501, *Hearing Conservation*—was published in 1980.[74]

Federal noise standards evolved similarly, and the DoD implemented standards to parallel the federal regulations. The Walsh-Healy Public Contracts Act, *Noise Standard*, published in 1969, was incorporated into The Occupational Safety and Health Act of 1970 (OSHAct).[75] The noise section contained fewer than 350 words, with a key provision that required a "continuing, effective hearing conservation program" whenever a table of allowable levels and durations was exceeded.[75] After a protracted process of debate and comment on the specific requirements necessary for this program, a final noise standard was published in 1983.[76] The DoD implemented the directives of the 1983 Federal Noise Amendment in an update of the DoDI, which was published under a new designation, DoDI 6055.12.[77] Including policy issues such as assigning specific responsibilities has upgraded the army's implementing document to DA pamphlet status, designated as DA PAM 40-501.[78]

Noise-Hazard Criteria

Most aspects of noise-hazard evaluation in the army mirror those in the private sector, although some aspects are militarily unique. Both in private industry and in the army's program, industrial hygiene personnel evaluate potential hazards with noise-measuring equipment that is calibrated to the standards of the American National Standards Institute.[79] Unique features of the army program include more stringent noise-exposure criteria and the pervasiveness of high-intensity, impulse-noise sources.

The army has established noise-exposure criteria according to the specific type of noise: (*a*) continuous, (*b*) airborne high-frequency and ultrasonic, and (*c*) impulse.

For continuous noise, the army employs a modified version of the DoD criterion: as exposure time is doubled, a 4-dB decrease in intensity is enforced or suggested. For example, 85 dBA (ie, a weighting network for hearing—conservation—exposure criteria) is hazardous for 8 hours, so 89 dBA is hazardous for 4 hours. These criteria have also been extrapolated for noise exposure for longer than 8 hours. The establishment of representative time-weighted averages (TWAs) for civilian and military personnel working in industrial operations is in progress. For the purposes of administering the Hearing Conservation Program, levels of steady noise of 85 dBA or greater are presently considered hazardous, regardless of the duration of the exposure.[70] Practical guidance to preclude misuse or overzealous implementation of a single-number criterion were provided in implementing documents:

> This criterion affords the advantage of increasing the overall efficiency of the program by simplifying its administrative aspects....It will also better protect

> those individuals who are more susceptible to the effects of noise. Although the requirements of the program demand the initiation of hearing conservation measures when levels are 85 dBA or greater, the implementation of all available measures may not be necessary in every case. For example, visitors to noise-hazardous areas are required to wear hearing protective devices, but the requirement for hearing evaluations does not apply to visitors. There may also be unique situations where noise levels rise infrequently and unpredictably to 85 dBA or greater for very short durations so that the wearing of hearing protective devices may be judged impractical or unnecessary. Decisions to waive the wearing of hearing protective devices or any other requirement of the program must not be made arbitrarily. Such judgments may be rendered by trained AMEDD [Army Medical Department] personnel who will perform a thorough evaluation using approved instrumentation and who will consider all factors relative to the potential for a given exposure to cause hearing impairment.[74(p3)]

Airborne High-Frequency and Ultrasonic Noise

Exposure to airborne high-frequency and ultrasonic noise occurs at army installations from various sources such as industrial cleaners and degreasers, dental drills and scalers, and aircraft compressors. The army has adopted the recommended Threshold Limit Values (TLV) of the American Conference of Governmental Industrial Hygienists (ACGIH) for potentially hazardous high-frequency and ultrasonic noise sources (Table 7-1).[80] Durations of permissible exposure are not included in these values, but only single-decibel levels in one-third octave bands are included. Decibel levels for one-third octaves above 20,000 Hz (ie, ultrasonic noise) were included to prevent possible hearing loss from the subharmonics of those frequencies that we do hear and that are generated within the ear. Equipment for measuring noise in the one-third octave bands is usually not available at local installations, but can be obtained from the USAEHA.

Impulse Noise

The impulse-noise exposures and the multiplicity of impulse-noise sources in the army environment dictate that the requirements of the hearing conservation program be mandatory. Where the Occupational Safety and Health Agency (OSHA) requires that exposures *should* not exceed 140 dBP (ie, criterion for exposure to impulse noise), the army dictates that exposures *must* not exceed this level.[74,75] Because the army uses small-arms ammunition (including blanks) that produce impulse-noise levels above 140 dBP, measures to conserve hearing must be instituted and enforced when weapons are fired during training.[74]

The single criterion of 140 dBP—notwithstanding several parameters—defines the hazard of impulse noise. These parameters include (*a*) peak decibel (or intensity) level, (*b*) frequency content, (*c*) number of impulses, (*d*) duration of each impulse, and (*e*) the angle of incidence of the incoming sound wave.

The higher the peak intensity, the more hazardous the noise.[81,82] Shoulder-fired, antitank rockets such as the Dragon can have peak intensities as loud as 185 dBP at the firer's ear. Artillery fire can exceed 180 dBP, depending on the charge, the length of the tube, the angle of fire, and the presence and type of muzzle brake. Mortars, depending on their charge and caliber, can produce intensities from 165 to 178 dBP. Rifle and pistol fire will measure 156 to 162 dBP at the firer's more exposed ear. Generally, the same peak intensity from artillery fire will be considerably less hazardous than that of rifle fire because artillery fire is of a lower frequency content.[83] The total noise hazard from shoulder-fired rockets was not great because they were expensive to test fire until simulators were developed that cost only pennies per shot.

The noise hazard also increases as the number of impulses increases over a given time.[81,82] As a general rule, the larger the caliber and the louder the weapons system, the fewer the impulses that are generated. In addition, the noise hazard increases with the duration of the impulse. Reverberations from reflected surfaces can lengthen the impulse.[81]

The angle of incidence also affects the severity of the noise hazard. The more the impulse impinges directly on the ear, the more hazardous it is. For example, the

TABLE 7-1

PERMISSIBLE NOISE LEVELS OF AIRBORNE HIGH-FREQUENCY AND ULTRASONIC RADIATION

One-Third Octave Band Center Frequency (kHz)	One-Third Octave Band Intensity Level (dB)
10	80
12.5	80
16	80
20	105
25	110
31.5	115
40	115

right ear (for right-handed shooters) is partially protected from the sound of the rifle fire by the "shadow" of the shooter's head.

All these factors are uniquely combined in mortar fire, which render it excessively hazardous to mortar crews. But the M16 rifle, because of its widespread use, potential rate of fire, and relative high-frequency content, has the dubious distinction of being the primary destroyer of hearing in the army.

Posting

The army emphasizes prominent posting of noise-hazardous areas and equipment with appropriate danger signs and decals.[74,84] For equipment that generates 85 dBA and 140 dBP noise-hazardous fields, signs must be posted to identify these contours.[74]

Although compliance is not guaranteed, a direct correlation has been observed between the presence of signs and the use of required hearing protectors.

Noise Controls

Engineering and administrative noise controls are essential components of a hearing protection program. Engineering controls are desirable; their use eliminates the noise hazard and renders other components of the Hearing Conservation Program unnecessary.[74] Administrative controls are generally employed when hearing protection cannot protect soldiers or civilian employees from a given exposure.

Noise reduction that employs engineering methods is based mainly on applying certain principles of the science of sound. Solving complex noise-control problems usually requires the services of acoustic engineers, who are available at the Bio-Acoustics Division of the USAEHA.[74] However, the industrial hygienist, audiologist, environmental scientist, or preventive medicine officer with a general understanding of acoustic principles can recommend measures that will often control many noise problems successfully.[74]

Engineering Controls

Engineering controls are used whenever feasible to reduce continuous noise to below 85 dBA and impulse-noise intensities to below 140 dBP (or to the extent possible).[74] Engineering noise control is generally feasible if implementation is practicable and cost effective, both technologically and operationally.[74] Engineering measures may involve significant expenditures, and thus

> installation planners must establish priorities so that available funds will yield the greatest benefits. Such priorities must be based on factors such as the number of personnel exposed to a particular noise source, future intended use of the facility, as well as the level and the duration of exposure.[74(p4)]

Two programs that complement engineering noise controls are the Health Hazard Assessment (HHA) process, which is discussed in detail in Chapter 6, Health Hazard Assessments, and the Quiet Tracked Vehicle Program (QTVP). The HHA process attempts to ensure that hardware design and procurements conform to both Military Standard (MIL STD) 1474 and medical policy for noise exposure, but all military materiel procured before the initiation of the HHA process were not subjected to any restrictions that may have been recommended through an HHA. Newly designed or purchased equipment, however, must exhibit the lowest possible noise-emission levels and conform to the acoustic noise limits prescribed in MIL STD 1474.[74,85]

Similarly, the QTVP has contributed to engineering noise controls. The high levels of noise produced by tracked vehicles have been a problem historically and are responsible not only for hearing loss, but also for both degraded communication and aural detection at great distances.[86–88] A 15-year effort has produced a compliant sprocket and an isolated roadarm and roundwheel to reduce the noise associated with tank movement. These innovations were incorporated into a demonstration vehicle; interior noise was reduced by 8 to 10 dBA and exterior noise by 3 to 4 dBA.[88] The durability of the reduced-noise suspension system is still under study.

Administrative Controls

Administrative controls to limit noise exposure are not always practical in army industrial operations. The characteristic understaffing of the federal civilian workforce can limit the use of administrative controls such as the rotation of workers through different job areas to limit noise exposures. These restrictions may be more practical in military training, however. For example, limits can be set on the number of rounds of ammunition fired or on the peacetime use of a particular weapons system.

In the design and procurement of equipment in the HHA process, administrative controls can limit the number of rounds fired by writing the appropriate guidance in the operator's manuals. These administrative controls are crucial; the nature of most noise sources evaluated in the HHA process has defied reduction through engineering. However, an aggressive approach toward engineering controls at the Fort Belvoir Research and Development Center has produced some positive results. Researchers at the center have reduced noise on new military equipment such as generators and water purifiers, which have counterparts in the private sector

Personal Protective Equipment

Protecting hearing in the army is doubly challenging. First, many noise sources are not amenable to engineering controls, which increases the wearers' reliance on hearing protectors. And, second, use of the Kevlar helmet dictates the use of earplugs, which creates a dilemma: unless an expert inspects the seating of the plugs, only the user knows whether or not they are inserted properly. Consequently, the emphasis on promoting the proper use and care of hearing protectors that was initiated over 20 years ago continues today.

Only personal protective equipment (PPE) that has been approved by the Office of The Surgeon General (OTSG) is authorized for use. The nomenclature and National Stock Numbers of approved hearing protectors are included in DA Pamphlet 40-501.[78] These protectors have been tested thoroughly for their attenuation characteristics, durability, and freedom from toxic effects. Not only have all commercially available devices not been tested in this manner, but they also cost considerably more than those that are ordered through army supply channels. The army uses a carefully selected set of hearing protectors (Figure 7-22) including (*a*) preformed earplugs (triple- and single-flange), (*b*) hand-formed earplugs, (*c*) ear-canal caps, (*d*) noise muffs, and (*e*) noise-attenuating helmets. All hearing protectors are issued gratis, and a freedom of choice among these approved devices is required by the DoD unless the choice is medically or environmentally contraindicated.

Preformed earplugs include (*a*) the triple-flange earplug, which predominates because of its ease of fit and consequent popularity among soldiers, and (*b*) the single-flange earplug, the V-51R, which was developed over 45 years ago, and is used as a backup plug for difficult-to-fit cases, particularly those soldiers whose ear canals are excessively crooked. Although both of these preformed earplugs are available in the private sector, only the military color-codes them according to size and mandates that all sizes be available for fitting and issue.

Although the army sometimes uses hand-formed earplugs of foam or silicone, those installations that use them in large numbers often distribute them without proper instruction. This is reflected in data that show increased hearing threshold shifts among large numbers of personnel who are reported to be hand-formed earplug users. Hand-formed earplugs are best used for visitors or other transient personnel who do not have their fitted hearing protectors with them at the time.

Although noise muffs, ear-canal caps, and noise-attenuating helmets are also approved for use, they are used less frequently. Installations with an industrial base should use more noise muffs, because they more effectively protect against intermittent noise. Noise muffs are available as safety devices and are worn with suspension systems over the head, behind the head, or under the chin. Authorization has been granted to

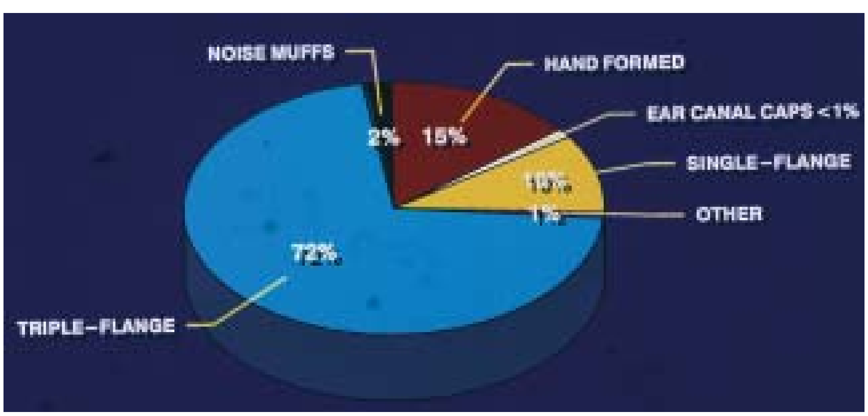

Fig. 7-22. The types of hearing protection used in the US Army. These data were obtained from 433,421 reference audiograms conducted from 1985 to 1989. Source: Donahue AM. *Hearing Conservation Data Profile*. Aberdeen Proving Ground, Md: US Army Environmental Hygiene Agency; 1991. Armywide database 51-34-0251-91.

purchase noise muffs from commercial sources. Commercially available recreational muffs with built-in radios are not approved for hearing protection. Sound levels from radio earphones may pose a potential auditory hazard as well as a safety hazard because warning signals may not be heard. In comparison, ear-canal caps are a medical item and are restricted to noise environments under 95 dBA.[74] Significant differences exist in the issue and maintenance of the two types of noise-attenuating helmets: aviator helmets (SPH-4 and IHADDS) and the armored-vehicle crew-member helmets (DH-132). Aviator helmets are items of individual issue, are fitted individually, and are well maintained, but the armored-vehicle helmets are not. Every time these helmets are checked in the field, between 30% to 40% of them are unserviceable because of missing or hardened earcup seals or missing chin straps or both.

Earplugs are invasive medical devices that must be ordered through medical-supply channels and, in the case of sized preformed earplugs, must be fitted under medical supervision.[78] In contrast to the private sector, where less than 20% of the occupational health–hearing conservation programs maintain records on hearing protectors, the army closely monitors sizing distributions.[89] Although neither of the sizing distributions shown in Figures 7-23 and 7-24 is considered ideal,

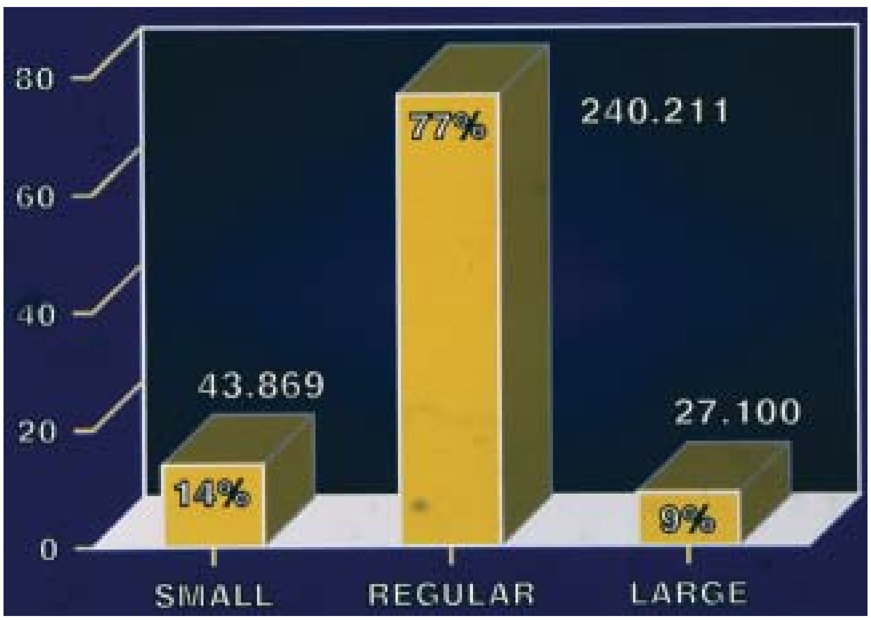

Fig. 7-23. The sizing distribution of 311,180 pairs of triple-flange earplugs fitted from 1985 to 1989. The Hearing Evaluation Automated Registry System (HEARS) program counts the size of the left earplug only. Source: Donahue AM. *Hearing Conservation Data Profile*. Aberdeen Proving Ground, Md: US Army Environmental Hygiene Agency; 1991. Armywide database 51-34-0251-91.

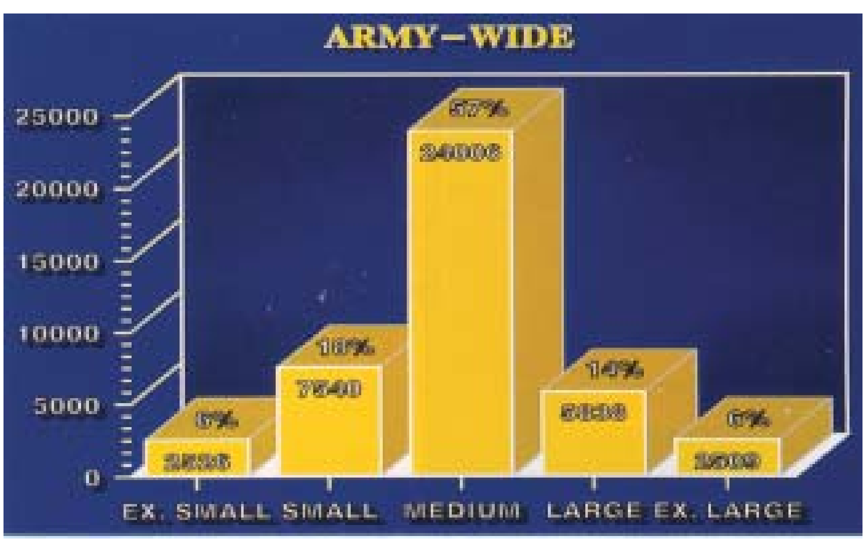

Fig. 7-24. The sizing distribution of 42,419 pairs of single-flange earplugs fitted from 1985 to 1989. Only the size of the left earplug was counted. Source: Donahue AM. *Hearing Conservation Data Profile*. Aberdeen Proving Ground, Md: US Army Environmental Hygiene Agency; 1991. Armywide database 51-34-0251-91.

data will be available in the next few years that will be used to issue standards on appropriate sizing distributions, depending on age and gender. For the present, trends are identified armywide and locally to monitor fitting procedures. For example, an increase in average age is expected with an increasing size of earplugs, and females are expected to be skewed toward the smaller sizes. The data available on the number of individuals who require a different-sized earplug in each ear are also suspect (Figure 7-25). Under carefully controlled fitting environments, at least 5% to 8% of personnel using the single-flange earplug have been found to require a different size in each ear. Only 1% to 2% of those who use triple-flange earplugs require different sizes.

Medical personnel are instructed in fitting techniques with an emphasis on comfort and proper seal. They are also taught to exploit and anticipate problems associated with the occlusion effect. For example, if earplugs (or other types of hearing protectors) are worn properly, the individual's own voice will sound lower in pitch to him or her. In addition, an individual's tinnitus will be more apparent when hearing protection is worn, particularly when the earplugs are fitted in a quiet clinic or classroom. Other issues such as excessive cerumen and the cough reflex are addressed in training materials.[90]

The army has developed an olive drab earplug carrying case that blends with the color of the battle dress uniform (BDU) and does not reflect light. Commanders should be encouraged to require that the case and earplugs be worn on the BDUs to ensure their availability.[74]

An earplug-insertion and -seating device is also included in the carrying case for the two preformed earplugs. The earplugs must be soft and compliant for the wearer's comfort and able to obtain a proper seal; however, individuals whose fingers are wide and blunt will have difficulty inserting their earplugs properly. Seating devices make insertion easier for these wearers (Figure 7-26) and improve noise reduction.[91]

Noise reduction ratings (NRR) that are obtained in laboratories with experimenter-supervised fittings have proven to be virtually worthless. Numerous studies have demonstrated the futility of attempting to predict protection in the workplace based on NRRs.[92–96] The army's approach uses (*a*) an approved set of high-quality hearing protective devices; (*b*) emphasis on proper fit and instruction; and (*c*) single-number, across-the-board limits for noise exposures. DA PAM 40-501 contains tables that detail these limits.

Theoretically, almost all noise-induced hearing loss that is incurred during routine training exercises is preventable if approved hearing protectors are properly used. However, an obvious gap exists between theory and reality: hearing conservation experts often say that the best hearing protector is the one that is *worn*. The expectation that protective devices will be worn only when the policy is enforced rather than when the devices are indicated may have been realistic for hearing conservation programs in their developmental stages. However, current army occupational health programs have reached a level of sophistication and, therefore, the expectation and provision of adequate hearing-protective measures should be raised.

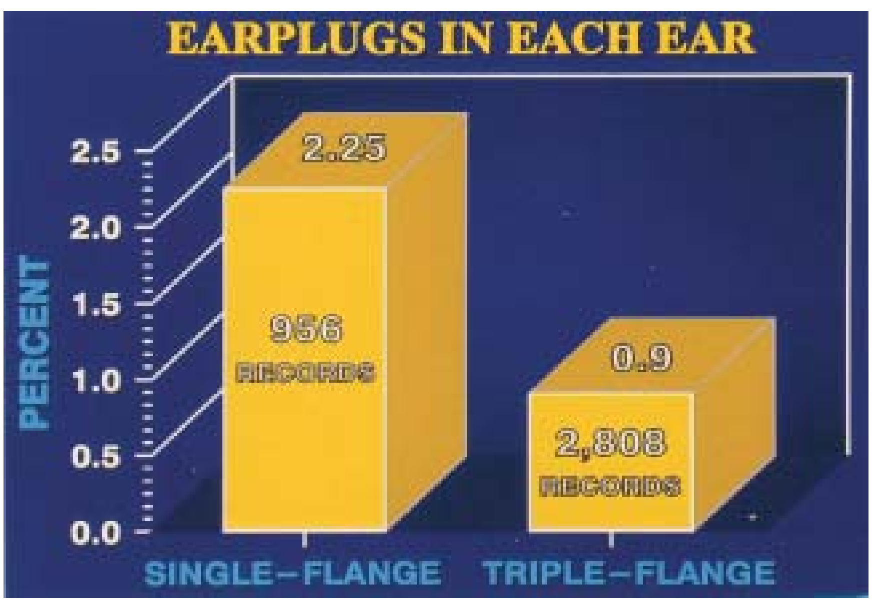

Fig. 7-25. These distributions pertain to the armywide data reported in Figs. 7-23 and 7-24. If they are fitted properly, the percentage of different sizes of single-flange earplugs should be at least 5% to 8%: 42,419 single-flange earplugs and 311,180 triple-flange earplugs from 1985 to 1989. Source: Donahue AM. *Hearing Conservation Data Profile*. Aberdeen Proving Ground, Md: US Army Environmental Hygiene Agency; 1991. Armywide database 51-34-0251-91.

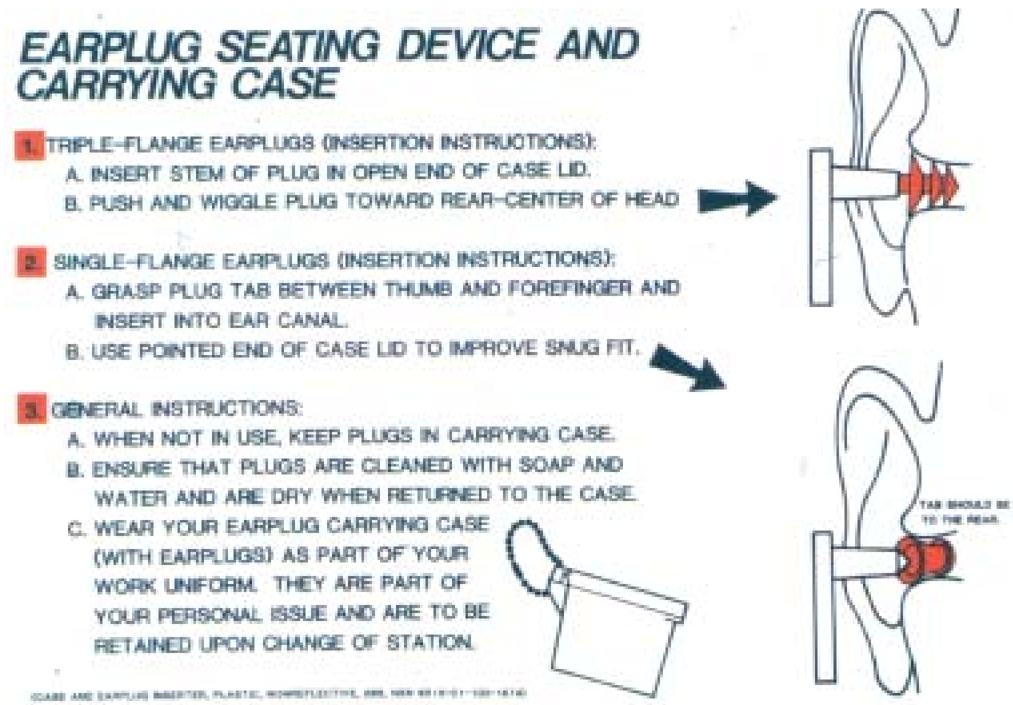

Fig. 7-26. This instructional poster provides insertion instructions and shows the seating device and carrying case for preformed earplugs. Source: DA Poster 40-501E, April 1991.

The Military Occupational Health Vehicle

Visits to fixed-site health facilities for medical surveillance can remove personnel from their jobs for up to one-half a workday. Military audiologists originally used military occupational health vehicles (MOHVs) with audiometric-testing capabilities to alleviate this problem at Forts Carson, Bragg, Knox, and Campbell. Multiphasic testing capability was developed in an MOHV at Fort Eustis. In the spring of 1988, the army fielded MOHVs with capabilities including audiometry, vision screening, pulmonary-function testing, blood-pressure screening, electrocardiography, and venipuncture to 16 major installations.

Hearing conservation activities occupy most of the space and the operation time of these MOHVs (Figure 7-27). An orientation room is used for fitting earplugs and for health-education activities that are facilitated by a television monitor, earphones, and a video cassette recorder.

Audiometric Monitoring

Audiometric monitoring detects changes in hearing sensitivity. Individuals who are susceptible to noise-induced hearing loss can be identified before their hearing sensitivity evolves into a communication handicap. In addition, statistical trends of hearing threshold shifts can be used to determine the effectiveness of hearing conservation programs.

The HEARS registry is a part of the Occupational Health Management Information System (OHMIS) and provides automated testing and data to a local manager's module. HEARS is also designed to transfer audiometric information from the installation to its armywide database. Quarterly, the HEARS database is compared to personnel tapes, and audiograms of former government employees are archived. The flow of information is circular, with the armywide database providing needed information to the installation manager's module and audiometer sites (Figure 7-28). Access to the database is limited to the OTSG, Health Services Command (HSC) Headquarters, and the functional proponent for the system, the Bio-Acoustics Division of USAEHA. Armywide and major army command comparative data are included in a user's guide. The operations of the HEARS audiometer and manager's module are detailed in USAEHA Technical Guides 167A and 167B.[97,98]

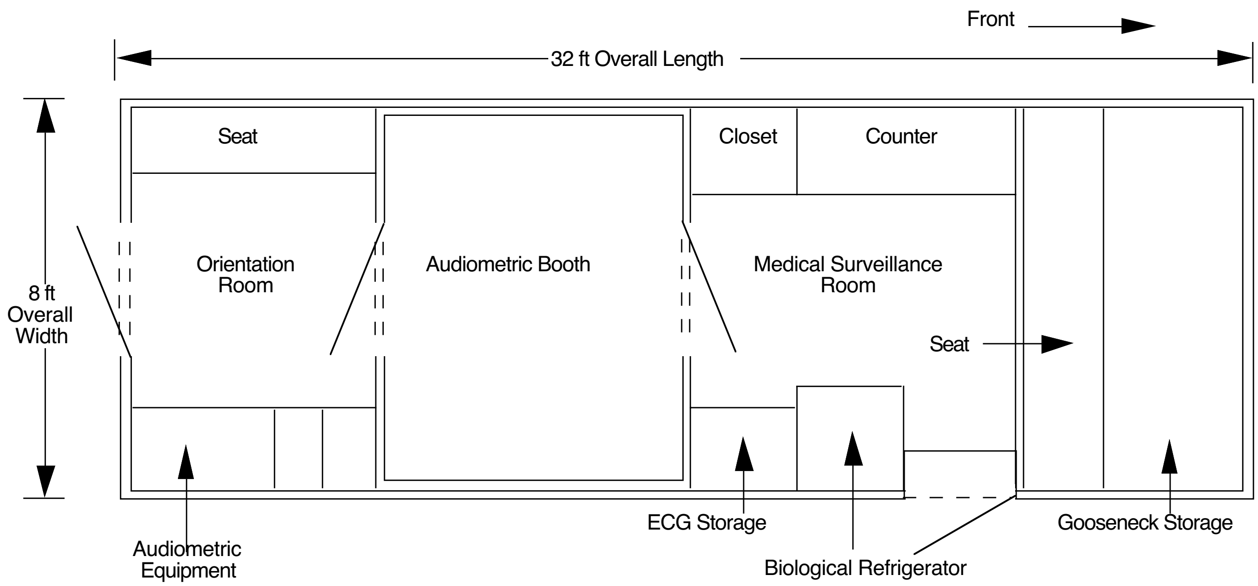

Fig. 7-27. An aerial view of the floor plan for the Military Occupational Health Vehicle (MOHV). When the MOHV is used exclusively for audiometric monitoring, six people can occupy the audiometric booth. Six others can be fitted with earplugs and briefed on hearing-conservation measures in the orientation room. Photograph: Courtesy of the US Army Environmental Hygiene Agency, Aberdeen Proving Ground, Md, 1991.

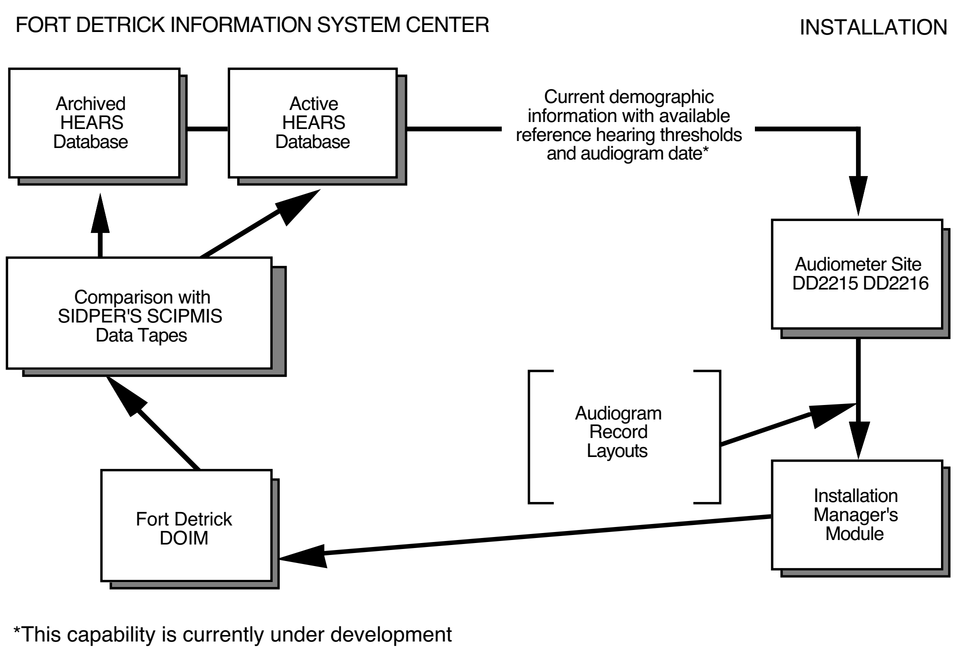

Fig. 7-28. HEARS data flow between Fort Detrick Information Center and the installation. Source: US Army Environmental Hygiene Agency. *Hearing Evaluation Automated Registry System (HEARS) Audiometer Operation Manual.* Aberdeen Proving Ground, Md: USAEHA; 1991. Technical Guide 167A. Available from the USAEHA, Bio-Acoustics Division, Aberdeen Proving Ground, MD 21010-5422.

Personnel Testing Requirements

All soldiers are required to receive reference and termination audiograms, and noise-exposed soldiers must also receive additional periodic testing (90 d after reference, annually, and any indicated interval for follow-up testing). Reference audiograms are used to

- monitor for hearing damage that is sustained during weapons qualification,
- serve as a baseline in the soldier's likely assignment to noise-hazardous duty at some point in his or her career, and
- provide a comparative population for soldiers who are routinely exposed to noise.

Since soldiers constitute a preselected population, comparisons to public health survey data or other databases in the private sector would not be epidemiologically valid.

Civilians who are exposed routinely to hazardous noise receive reference, periodic, and termination audiograms and are included in the HEARS database; however, all others must be excluded to avoid corrupting the database. Deaf civilians who work in hazardous noise environments must receive, at a minimum, reference and termination audiograms. Although the possibility that deaf personnel will incur additional hearing loss from noise is extremely remote, most have some residual hearing that should be documented for medical and legal purposes.

Audiogram forms designed specifically for DoD Hearing Conservation Programs are available for the clinical management of individuals in the program. The DD form 2215, *Reference Audiogram*, and the DD 2216, *Hearing Conservation Data*, were developed from U.S. Air Force forms in the late 1970s. Automation and recent changes in Hearing Conservation Program requirements have provided the impetus for forms revisions, which are imminent.

The HEARS audiometer prints completed audiograms for the health record and creates a record layout file of relevant fields for uploading into the manager's module and into the HEARS armywide database.

Variables in Audiometry

Accurate audiometric evaluation of military personnel has historically not been emphasized in policy directives. The army's documentation of widespread invalid test results in the past testifies to its lack of attention to, and limited appreciation of, the variables that must be controlled during a hearing evaluation.

Hearing is not tested directly with the conventional pure-tone threshold audiometry used for hearing conservation surveillance, but by interpreting a behavioral response to a pure-tone stimulus. Test results reflect the adequacy of the test environment, the instructions that are provided, the threshold technique that is used, the calibration of the audiometer, and the motivation of the examinee. The HEARS audiometer includes several features designed to control for, but not to eliminate, these variables.

Audiometric technicians are required to have successfully completed a minimum of 3 days of training specified by the Council for Accreditation in Occupational Hearing Conservation (CAOHC),[99] whether they are corpsmen, nurses, or health technicians. Although physicians and audiologists are excluded from such training requirements, they should be aware of the salient elements of an audiometric technician's training.

The HEARS audiometer is configured in one-, two-, four-, six-, and eight-station units. A talk-over mode permits supplemental instructions for individuals who experience difficulty during the test. Fault codes alert the technician if an examinee is not proceeding appropriately, and recommended instructions are available on the screen monitor.

The HEARS audiometer employs a threshold-determination technique, based on a psychophysical method of limits that is best understood as a bracketing procedure. For example, the threshold search begins at 0 dB HTL at 1000 Hz, and increases in 10-dB increments until the subject responds. Another tone presentation at that decibel level confirms the examinee's initial response and provides a reinforcing auditory image of the stimulus. The level then decreases 10 dB for every response and increases 5 dB for every nonresponse. Three responses at one dB level are accepted as threshold. This technique, called the modified Hughson-Westlake method, is the most accurate method in use and is recommended by the CAOHC.[99] In the automatic mode, this process is done for the operator. For difficult-to-test examinees, however, a manual mode is available, during which the examiner has control of the interstimulus interval, the order of the test frequencies, and the level of the initial tone presentation.

Currently, the HEARS audiometer cannot test hearing below 0 dB HTL, although some individuals may be able to hear below this level. Future considerations include a modification (ie, a firmware change) to a microprocessor chip in the audiometer, to add this capability.

The pulsed-tone mode is defaulted on the HEARS audiometer unless the continuous-tone option is selected. Pulsed tones can be followed more easily, particularly for individuals with tinnitus: they can separate the pulsed tone from their perceived constant ringing sensation. Three tones, 200 msec each, with a 50% duty cycle (ie, 50% of the time the tone is on, and 50% of the time the tone is off) are presented. The examinee is allowed 1.8 seconds to respond from the onset of the stimulus, hence the need for a prompt response.

HEARS provides automatic retests to establish the validity of the data for a variety of conditions. The standard retest at 1000 Hz must be within 5 dB of the first threshold or thresholds obtained at other test frequencies will be suspect (eg, learning may have occurred or the examinee may have been inattentive). Other conditions that prompt an automatic retest include

- a 50-dB difference in threshold between adjacent test frequencies,
- a threshold greater than 30 dB at 500 Hz,
- any threshold greater than 90 dB HTL,
- test frequencies that time out (ie, take longer than 30 seconds for the examinee to determine the threshold), and
- any test frequency 1000 to 4000 Hz with a 20-dB or greater shift in either direction from the baseline.

HEARS uses automatic calculations to limit technician error and to save processing time. For example, hearing thresholds are determined from the appropriate number and sequencing of responses, stored in the computer's memory, and printed on demand. Similarly, the HEARS audiometer calculates military hearing profiles, as detailed in AR 40-501.[100] If a reference audiogram is performed before noise exposure and entered into HEARS, the profile system for an induction physical is activated. The percentage of hearing loss based on the DOL formula is calculated for civilian personnel and printed as a percentage of binaural impairment.

Periodic test results are compared to reference thresholds and significant threshold shift (STS) is calculated. Positive STS (ie, hearing loss) is confirmed using OSHA criteria, which state that shifts an average of 10 dB or greater at 2000, 3000, and 4000 Hz in either ear is an STS. The National Institute for Occupational Safety and Health (NIOSH) age corrections for males and females are also incorporated for positive STS. Hearing loss attributable to the aging process is subtracted from the threshold shift. Age corrections are not applicable to a negative STS (hearing improvement).

Diagnosis and Patient Disposition

Army policy is to use positive TTS as a marker for individuals who are susceptible to hearing loss, for those who are not in compliance with the regulations regarding the use of hearing protection, or both. Since quiet periods are not required before a periodic test, some STS could be temporary. Follow-up testing confirms positive STS.

The first follow-up audiogram must be performed within 30 days of the identified STS, with a minimum of 15 hours before the test free of hazardous noise. If positive STS persists, the individual's supervisor is notified and a second follow-up examination is required, which must be preceded by at least 40 hours free of hazardous noise after the first follow-up audiogram.

After all required follow-up testing is performed, diagnostic testing helps the otolaryngologist determine the site of the lesion that is causing the hearing loss, but not necessarily to lower thresholds and defer the reporting of permanent STS. Obviously, clinical judgments must be made in cases of malingering or questionable audiometry on which the referral was based. Early detection serves the best interest of noise-exposed personnel, and in the long run, makes less work for medical personnel. Negative STS averaging 10 dB or greater at 2000, 3000, and 4000 Hz indicates, most probably, an invalid reference test. When there is a negative STS on the first follow-up, the audiometric results from that follow-up may be used to establish a new reference test. Audiological and otological referrals are optional in cases of negative STS, and referrals are only indicated if test results of the first follow-up test are questionable. Details on notification and reporting of STS, as well as procedures for reestablishing the reference audiogram are included in the HEARS Operations Manual.[97]

The practice of referring an individual for diagnosis before all follow-up testing is complete on the HEARS audiometer is not advisable. Audiologists and ear, nose, and throat (ENT) technicians may feel a responsibility to lower thresholds by performing follow-up testing on a diagnostic audiometer. However, such well-meaning intentions raise the following issues: (*a*) using the diagnostic audiometer defeats the purpose of monitoring audiometry and delays early detection of hearing loss, and (*b*) in a diagnostic setting, most testers can lower an individual's threshold at a particular test frequency by 5 dB. Although the hearing shift may no longer total enough for an STS, a 5-dB window is still within test-retest reliability. Moreover, the primary purpose of follow-up testing is to rule out TTS from noise exposure.

Physician involvement in STS follow-up testing procedures focuses primarily on the diagnosis and any recommendations regarding patient disposition. Only physicians can diagnose noise-induced hearing loss, and they should use all reasonable methods of differential diagnosis before establishing this diagnosis, including

- an investigation of the individual's auditory history and previous hearing tests;
- pure-tone, air-conduction measurements (which measure outer- and middle-ear conduction);
- pure-tone, bone-conduction measurements (which measure inner ear function, bypassing the outer and middle ears);
- speech-reception thresholds;
- speech-recognition measurements;
- oto-immittance testing (which measures the impedance of the middle ear and tympanic membrane); and
- masking, when indicated (which isolates and distracts the ear with normal hearing in order to examine the other ear).

The disposition and profiling process for hearing loss differs for military and civilian personnel. Military personnel should be issued a profile for hearing loss, if indicated. Profiling procedures are listed on DA Form 3349 (Block 1), *Medical Condition-Physical Profile Record*, and in AR 40-501.[100] Disposition of military personnel who have sustained hearing loss is defined within the profile system.[100] For the final disposition of DA civilian personnel, Standard Form 513, *Clinical Record Consultation Sheet*, is used. Guidance for civilians who have sustained progressive hearing loss is less well defined and involves case-by-case evaluations and close coordination with civilian personnel officers.

A civilian employee's removal from, or assignment to, a noise-hazardous job poses a dilemma for the occupational health physician, who must first consider the army's general philosophy for civilian employees: hearing loss is not in itself a contraindication to the assignment of these individuals to noise-hazardous work, provided the employees are protected against further hearing impairment. The army makes the job safe for the worker. However, the physician must consider whether the individual will be a hazard to him- or herself and others. The physician is also obliged to work within the guidelines that exist for protecting the handicapped from job discrimination and with a Civilian Personnel System that is obligated to find another job, which has equal opportunity for advancement, for an individual who is removed from a noise-hazardous occupation.

Unfortunately, an inability to meet the communication requirements of a job can only be inferred from clinical test results. Such a disability is not easily documented. Direct measurements of the relationship between hearing loss and job performance are virtually nonexistent.[101] A strong recommendation that a worker be removed from a job may be made if tests demonstrate that the individual cannot hear vital acoustic warning signals. But, obviously, modification of the warning system should be considered first.

During the diagnostic and referral processes, the issue of hearing loss compensation is sometimes raised. Although the physician is bound both ethically and legally to inform individuals of their hearing losses, only those offices and agencies charged with the administration of these programs are authorized to assess compensability. Regardless of the physician's intentions, estimating a patient's potential compensation could create credibility problems if the physician's predictions are not borne out by the actual proceedings.

Evaluation of Hearing Conservation Programs

The ability to generate numerous audiograms or to distribute thousands of hearing protectors does not accurately measure the effectiveness of the army's Hearing Conservation Programs. Only statistical trends of hearing loss can objectively measure whether hearing protectors are being fitted and worn properly and faithfully. The most useful way to evaluate a program is to focus on the Hearing Conservation Program results, not just on the testing procedures—on the goals of the program, not on the details of its operation.[102]

Statistical trends of hearing loss, participation in monitoring audiometry, and quality-assurance measures can help to identify and improve ineffective programs. Such measures can educate medical and command personnel and also be a source of satisfaction and reward for units or installations that promote effective programs. For over 10 years, HEARS has been providing comparative data to installations and major commands. Requirements for local program evaluation have recently been instituted.[78]

Major army installations and medical centers have one HEARS unit designated as a manager's module. The HEARS manager's module has additional computer storage capability. The software allows management to analyze data on participation in the Hearing Conservation Program, its effectiveness, and quality-assurance information on demand. In addition to 71 standard reports, the manager's module also includes a nonprocedural language and a utility called TABLETALK that is used to produce ad hoc reports.

Program Compliance

The number of individuals who work in hazardous-noise environments (the denominator) can be compared to the number of individuals who are tested (the numerator) to measure compliance in monitoring audiometry. Twenty standard reports are available that can be used to identify the number and specific individuals tested. These reports include

- the number of tests administered,
- a list of names and social security numbers (SSN) by audiometric test date,
- record summaries by ZIP codes (counts of types of tests administered for military and civilian personnel),
- distribution of individuals by job code,
- serial hearing threshold data for individuals,
- retrieval of all DD 2215 or DD 2216 forms for an individual,
- a list of individuals who failed to take their annual tests,
- a list of individuals with STS on their periodic tests who require follow-up testing, and
- data regarding test counts by the audiometric technician's SSN and by the serial number of the audiometer to monitor work-load data by individual or test site.

Personnel turnover must be considered in assessing an installation's rate of participation. Also, the requirements for 90-day reestablished reference audiograms and termination audiograms should yield a 110% to 140% rate of participation if these additional tests are included in the numerator.

Quality Assurance

Checking for errors, automatic retests, automated calculations, and automated data-entries through HEARS have controlled quality-assurance measures significantly. Twenty-one standard reports are available on the HEARS manager's module to monitor potential problem areas. Although standards are still being developed for most of these measures, trends can be identified and armywide comparative data are available. The quality-assurance capability of HEARS allows it to generate reports concerning

- the same threshold at all frequencies that are tested,
- the absence of threshold entries at 0 dB,
- no reestablished reference audiogram,
- an elevated threshold at 500 Hz,
- a negative threshold shift,
- earplug sizes that vary by the type of protectors that are used,
- the need for different sizes of earplugs in each ear,
- types of hearing protectors in use, and
- multiple reference audiograms.

The quality-assurance reports are designed to check for a variety of potential problems:

- data fabrication,
- acoustic-calibration deviations,
- excessive background noise in the testing environment,
- invalid reference audiogram, and
- improperly fitted preformed earplugs.

Program Effectiveness

Unless otherwise specified, all of the 30 possible standard reports of program effectiveness can be run either separately for military and civilian personnel, or can be run according to ZIP code, job code, hearing protector, location (building number), or unit identification code (UIC). However, data from any report on program effectiveness will be of limited usefulness if there is poor participation (particularly among senior military personnel), poor quality control of the audiometric data, or a lack of follow-up testing to confirm whether an observed hearing threshold shift is permanent or temporary. Sources of program-effectiveness reports include (*a*) military profiles, (*b*) civilian hearing loss and potential compensation costs, (*c*) hearing threshold shifts, and (*d*) hearing threshold–level matrices. A hearing threshold matrix includes distributions and averages of hearing threshold levels.

When military profile reports are calculated, the most recent hearing test in the database is used. A discrepancy will exist between those profiles that are actually calculated and those that are assigned to individuals. Similarly, the most recent hearing test and pay grade are used to calculate hearing-loss percentages and potential compensation costs for civilians. The options to report the data in rank order either by cost or by the percentage of hearing loss are also included. These reports are limited to senior medical and command personnel only. Hearing threshold shift can also be calculated by the OSHA

STS, or by other measures of threshold shift that combine military and civilian personnel.

Health Education

The characteristics of noise-induced hearing loss make it a difficult subject to teach in health education. Noise-induced hearing loss is generally a slow, painless, and bloodless process. Hearing loss from noise is insidious and is not always recognizable to the individual until the magnitude of the loss has reached moderate-to-severe levels. The challenge to occupational health educators becomes apparent when placed in the context of the Accident Prevention Formula of the NSC: *See the hazard, Understand the defense, and Act in time*.

Nothing regarding noise-induced hearing loss is tangible. If an ear were to shed a drop of blood for every decibel of hearing that was lost, the task of identifying the hazard would be considerably easier. The usual progression of a noise-induced hearing loss from the high frequencies down into the low (or speech) frequencies can prevent an individual from quickly recognizing a problem and implementing timely action to prevent additional loss. But, as in the case of weapons fire, there may be no second chance. One afternoon on a firing range can wreak havoc on unprotected ears.

"Understanding the defense" against noise-induced hearing loss is not any more clear than "perceiving the hazard" to some of the individuals who are at risk for it. Most soldiers have been taught since childhood never to put anything into their ears; they now may simply be handed a pair of earplugs when noise becomes a hazard, without being instructed on their use. A complete and thorough military or civilian health-education program requires that (*a*) the students overcome behavioral obstacles or stereotypes, (*b*) the program's importance is emphasized by both command and management, (*c*) the importance of acute hearing for combat effectiveness or for the efficient performance of duties is stressed, and (*d*) the proper training aids and approaches are utilized.

Behavioral Obstacles

A lack of concern for hearing conservation can best be understood and addressed, both in the army and in the civilian-industrial sector, as a behavioral problem. Prevailing attitudes can frustrate the best-intended efforts to protect hearing. A preventable occupational injury that occurs on a large scale testifies not only to the pervasive nature of noise but also to the resistance against both hearing education and wearing hearing protection. Current challenges facing personnel who enforce hearing conservation include (*a*) auditory regression, (*b*) anatomical misinformation, (*c*) adaptation, (*d*) noise that is wrongly equated with power and efficiency, (*e*) denial of the hazard, (*f*) production of noise for social recognition, and (*g*) misplaced priorities.

Hearing has regressed in its importance to everyday life. Before artificial light was invented, during ages of nearly universal illiteracy, humans, like other mammals, relied heavily on their ears for information.[103] But with the advent of artificial light and the scientific revolution, learning became primarily visual. Today, the emphasis is on speed reading and visual scanning. How does this sensory shift affect our lives? Problems with sensory processing are generally tolerated until they become visual:[103] because aircraft noise does not assault the eyes, it may be tolerated until it interferes with television reception.

Among the medically unsophisticated, hearing deficits are associated with malfunction of the ear canal and the eardrum and the accompanying erroneous belief that noise-induced hearing loss is medically treatable. For example, some may believe that "noise only pokes little holes in your eardrums and old Doc can patch them up again," or that "noise can build up extra layers of skin on your eardrum and you can toughen your ears up to noise." Others have misinterpreted the limited benefits of cochlear implants, thinking that nerve cells can be restimulated back to life. Individuals may also believe that a hearing aid will be a perfect substitute for any hearing they have lost. Some in the medical community take the opposite and equally erroneous view that hearing aids cannot provide any benefit to those with high-frequency–noise-induced hearing loss. In addition, because the layman's knowledge of the ear does not usually extend beyond the outer ear, health-education activities should refer to *hearing* protectors, rather than *ear* protectors, when protective measures and equipment are discussed.[74]

Noise may damage physical health, but psychological adjustments are made to adapt to the noise. Adaptation is a two-edged sword; it can be a saving grace, but at the same time it may create a false sense of well-being.[103] The obvious danger of adaptation to noise is that our ability to recognize warnings of hazardous noise is lost, and we will no longer react to the hazard.[103] Similarly, TTS may give the individual a false sense of security when previous hearing acuity appears to have recovered after loud noise exposures.

The noise a machine makes may erroneously be equated with its power and operational efficiency.[103] Without a noise accompanying a function, consumers often believe that power and efficiency have been lost. For example, some consumers may believe that a whisper-quiet vacuum cleaner is not as powerful as an identical but noisier older model, and office workers have complained that after their typewriters' clacking sounds were removed, they were noticeably slower than their noisier, but otherwise identical, typewriters.[103]

A reluctance to wear personal protective devices may be a mechanism for coping with the day-to-day hazards of an occupation: the worker is able to deny that the hazard exists if the protective equipment is not used. A form of denial may also be observed in those soldiers who exhibit "macho" behavior. Although denial may be more prevalent with life-threatening hazards, reactions like these to loud weapons fire are not uncommon. Denial among young soldiers may be transformed into feelings of indestructibility, which is a common trait of youth. In basic training and advanced individual training, intimidation is often used to break through attitudes to ensure hearing protection compliance. However, in duty assignments that have less supervision, compliance with proper and faithful use of hearing protection may become more lax.

Senior personnel offer greater challenges to health educators than do younger soldiers. Higher-ranking soldiers who have lost hearing may choose to ignore their deficits, hoping that others will as well. Their attitude seems to be that since they have already lost their hearing, there is no reason to wear hearing protectors. Obviously, they should be convinced both to protect the hearing that they still have and to set an example for their subordinates.

Making noise can be an attention-seeking behavior that results in at least temporary recognition by peers. For example, among youths whose unmuffled cars or motorcycles signal their arrival at and departure from a scene,

> such cacophony gives them a feeling of being part of the "in" or "hip" crowd. . . . It can also be interpreted as a protest against the establishments' highly organized, dull, quiet world.[103(p8)]

Young people with limited communication skills may prefer simple words and gestures through the raucous din. Noise also offers an opportunity to invade another person's space and get much closer while talking than might otherwise be acceptable.

Other priority issues in the world—drug abuse, crime, budget deficits, homelessness, hunger, and terrorism—overshadow noise-induced hearing problems. Understandably, a commander's priorities are similarly ordered. Encouraging and enforcing compliance with hearing conservation principles is difficult in a militarily unique or industrial environment that is fraught with life-threatening hazards and demanding training and production schedules. Commanders may use "realistic training" as their excuse for not enforcing the use of hearing protection. In addition, the requirement to report for an annual hearing test may be thought of as a detractor from training.

Command and Management Emphasis

Because most noise-induced hearing loss occurs during routine training exercises, it should be almost completely preventable. A concerned commander can have a dramatic effect on a Hearing Conservation Program. Health education must be provided for command personnel and for all levels of supervisory personnel in order to emphasize their responsibilities in the Hearing Conservation Program. Without their endorsement and support, the program will not succeed.

The value of the program can be emphasized in several contexts, but most importantly, the application and implementation of a Hearing Conservation Program is the *law*. In addition to existing OSHA, DoD, and DA regulations, the Federal Employee Reform and Tort Compensation Act holds federal supervisors liable if they are found negligent and not operating within the scope of their authority to provide protective equipment. Even supervisors who provide the required hearing protectors may be under the erroneous assumption that the soldier or employee can choose whether or not to use the protectors. Responsibilities to enforce the use of PPE and to ensure that subordinates report for scheduled hearing tests can be included in officer and enlisted evaluation reports and in civilian supervisors' performance standards.[104]

Command and supervisory personnel may recognize the value of a program for hearing conservation when it is explained in terms of reducing compensation expenditures or saving lost man-hours that are caused by accidents. One study found that the risks attributed to noise and hearing loss together accounted for 43% of injuries sustained in one shipyard.[105] This study identified factors that could interfere with the faculties that are needed for recognizing warning signals and imminent danger. The use of hearing protection was not identified as a factor.

Combat Effectiveness

Senior commanders usually recognize that a Hearing Conservation Program is valuable to soldiers and civilian workers. Focusing on hearing as our most precious social and learning sense may be of limited value to many command and supervisory personnel unless the necessity to preserve hearing is incorporated into the success of their mission. For example, the flight surgeon responsible for medical planning on the Son Tay prison camp raid in Vietnam insisted that all troops wear earplugs while being airlifted. As a result, when the troops arrived at the prison camp and removed their earplugs, they found that their hearing was unimpaired from the noise of the helicopters.[90]

On today's high-technology battlefield, good hearing is a combat multiplier and an essential attribute of the effective soldier in both offensive and defensive operations.[78,106] Hearing is necessary in offensive operations to (*a*) locate snipers, (*b*) locate patrol members, (*c*) identify vehicles, and (*d*) determine types of booby traps. One Vietnam veteran reported that enemy snipers could be located by the reports of their weapons, even when muzzle flashes were not observed. In addition, patrol members often guide more by sound than by vision, especially when they are on night patrol under a new moon. Soldiers have also been able to hear the difference between hostile and friendly fire. The ability to determine the number and location of enemy vehicles may be crucial to the successful completion of a mission.

One Vietnam veteran could distinguish between the sounds generated by two types of trip wires. The sound generated by a trip wire that pulls the pin from a grenade is different from the sound made by a pressure-activated explosive. Quick movement away from the grenade is required, but the soldier must maintain pressure on the explosive until it is deactivated.[106]

In defensive positions, the soldier needs to hear both perimeter alarms that are activated by sensing devices that have been triggered by movement, and enemy movement through leaves, grass, and twigs. Experts have recognized the high-frequency nature of these sounds and the necessity for relatively normal hearing to detect them. Soldiers can determine the enemy's location by listening for sounds from wildlife, loading cartridges, safety locks, and the clipping of barbed wire. In Vietnam, soldiers could determine the proximity of the enemy by the cessation of bird calls in the upper canopy of the jungle. The presence of birds in the lower canopy meant that human refuse was nearby.

Soldiers must also be able to hear radio messages and verbal orders. Most military radios clip both the high- and low-frequency sounds. A soldier with a hearing loss will confuse similar-sounding verbal orders, such as the digits in a grid coordinate. Good hearing also aids in small-arms accuracy and weapon identification. Soldiers on pistol and rifle teams have been aware of the advantage of wearing hearing protection while firing their small arms. Wearing hearing protection increases their accuracy by reducing the tendency to flinch at the impact of the weapon and normal hearing can discriminate between M16 and Soviet-made AK47 rifle fire.

Performance Measures

Until recently, the relationship between the ability to communicate and the successful accomplishment of missions could only be suggested from anecdotes or inferred from vague clinical test results. A landmark study from the U.S. Army Human Engineering Laboratory has provided the first hard data of the effects of communication on performance.[101] Thirty experienced tank crews conducted gunnery exercises in the Conduct of Fire Trainer (COFT) tank simulator at Fort Knox under five communication conditions ranging from very good to extremely poor. Performance measures and results indicated that

- the mean time to identify a single target increased as communication conditions were degraded.
- the overall time to complete a firing mission varied from 40 seconds under good communication conditions to 90 seconds under the poorest conditions.
- target identification varied from a hit rate of 98% under the good conditions to 68% under the poorest conditions. The percentage of enemy targets killed also decreased as communication was degraded (Figure 7-29).
- commands communicated incorrectly varied from 1% to 37% over the range of communication conditions. As a result, the percentage of time the crew was killed by the enemy ranged from 7% under good communication conditions to 28% under the poorest conditions. Figure 7-30 shows the percentage of fire that hit the wrong target.[101]

Training Aids and Approaches

Effective health education will result in or reinforce the faithful and proper use of hearing protectors. Compliance with hearing conservation measures is individualized highly for both the military and the civilian sector.

Personal testimonials from peers or respected senior personnel on the dehabilitating effects of their hearing loss or the importance of hearing in combat may be effective as teaching tools.[107–111] For example, the film *Sounds of Combat* was introduced by a sergeant major and Medal of Honor winner.[107] Individuals like these have credibility with soldiers when they attempt to link good hearing to the success of a combat mission.

Individual counseling can be most effective, particularly when it is personalized. Demonstrating to a 30-year-old sergeant that he has the hearing of an 80-year-old man can be convincing. Training aids, unique to the military and designed for this purpose, are available through publication and audiovisual support centers.

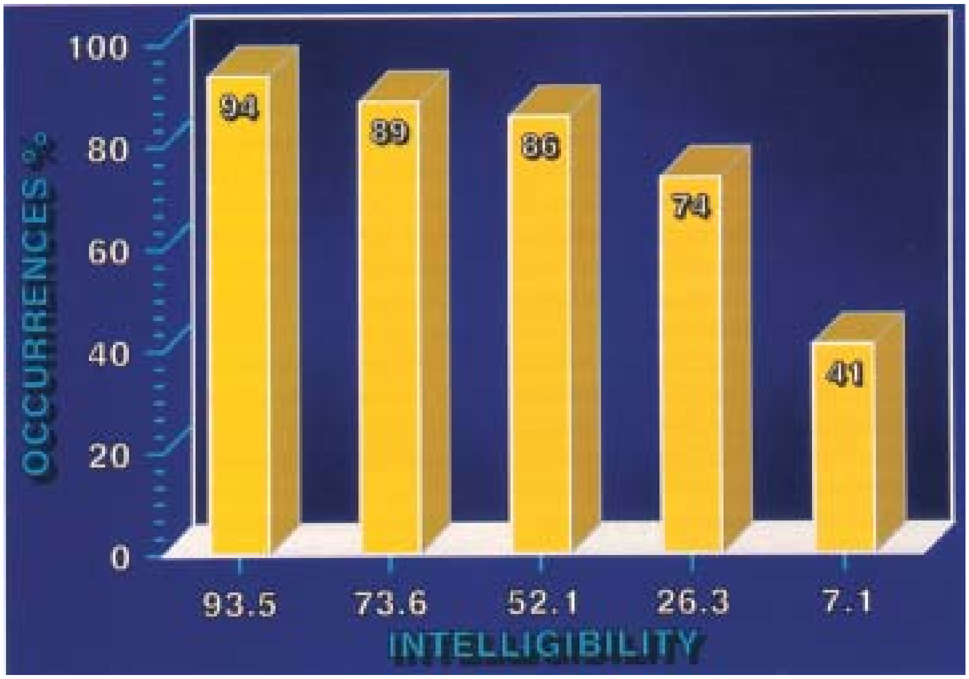

Fig. 7-29. Performance measures as a function of five conditions of speech intelligibility. For 30 experienced tank crews in a tank simulator, as their speech intelligibility was degraded their killed targets also decreased. Source: Garinther GR, Peters LJ. Impact of communications on armor crew performance. *Army Res, Development, & Acquisition Bull.* 1990;January-February:1–5.

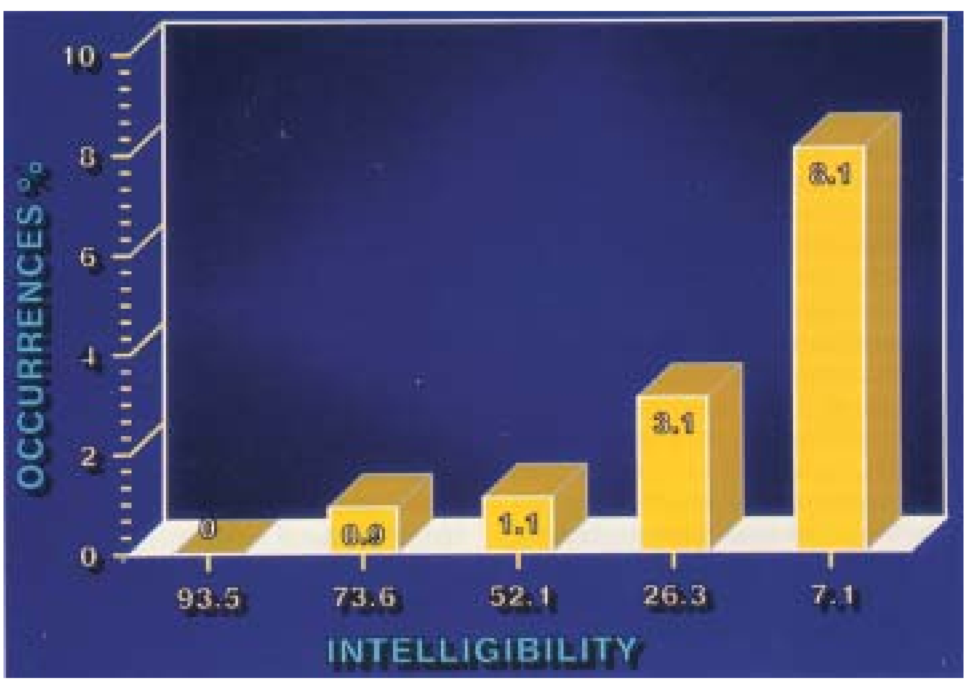

Fig. 7-30. Percentage of episodes in which the wrong target was shot as a function of the five conditions of speech intelligibility. Source: Garinther GR, Peters LJ. Impact of communications on armor crew performance. *Army Res, Development, & Acquisition Bull.* 1990;January-February:1–5.

SUMMARY

Noise-induced hearing losses can occur painlessly, are preventable, and will become permanent if effective hearing conservation programs are not enforced. The effects of noise on the complex auditory mechanism depend on the physical characteristics of the noise stimulus, the duration of exposure, the audiometric frequency, and the type of noise.

Factors that account for varying degrees of susceptibility to the hazardous effects of noise are under constant investigation. The dynamic processes and intricacies of the auditory mechanism make it impossible to formulate the exact relationship between the noise exposure, the receiver, and the amount of hearing loss that is sustained. Awareness of changes in the auditory mechanism following exposure to hazardous noise should assist the physician in evaluating cochlear function.

The army attempts to prevent hearing loss through the coordinated application of several program elements. No single program element can function effectively without all the other elements, which include

- noise-hazard evaluations,
- posting of noise-hazardous areas and equipment,
- engineering controls,
- use of PPE,
- audiometric monitoring,
- health education, and
- Hearing Conservation Program evaluation.

Effective hearing conservation programs are characterized by well-defined responsibilities among participants, and the presence of a single individual who functions as both a catalyst and a linchpin to ensure the implementation and the coordination of all program elements. The program is best implemented as a facet of combat-readiness medicine, with hearing preservation incorporated into the overall success of the mission.

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