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Understanding and preventing noise-induced hearing loss

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Introduction

Noise is a major occupational and environmental hazard, causing hearing loss, annoyance, sleep disturbance, fatigue, and hypertension. Although the extra-auditory effects of high-level noise exposure have been reported, noise-induced hearing loss (NIHL) has long been recognized as the primary and most direct health effect of excessive noise exposure.[1] The World Health Organization reported that 16% of the disabling hearing loss in adults is attributable to occupational noise exposure.[2] NIHL has been recognized as an occupational disease and injury since the 18th century among copper workers who suffered hearing loss as a result of hammering on metal.[3] In the 1800s, Fosbroke[4] also mentioned how blacksmiths suffered hearing impairment from continued exposure to noise.

The occupational risk of NIHL in industries that expose workers to continuous high levels of noise is well established with more than 30 million U.S. civilian workers estimated to be exposed to potentially damaging noise levels and another 9 million at risk from other ototraumatic agents, including chemicals.[5] In 1996, the NIOSH had established the National Occupational Research Agenda (NORA) that identified NIHL as one of the 21 priority areas to stimulate innovative research and improved workplace practices to reduce NIHL problem. In order to manage this major health problem among workers exposed to occupational noise, it is important to understand the nature of NIHL.

Two characteristics of NIHL have been thoroughly established through numerous studies. First, the amount of hearing loss increases with noise intensity and duration of exposure, such that more intense and longer-duration noise exposures cause more severe hearing loss. Second, individual susceptibility to NIHL varies greatly. Not all individuals exposed to a given noise level develop the same degree of hearing loss.[1,6] Although the reason that some individuals are more susceptible to NIHL than others is not well understood, several factors have been implicated, including age, previous sensorineural hearing loss, cigarette smoking, use of ototoxic medication, type 2 diabetes, and hypertension.[1] The relationship between these factors and NIHL works in reverse as well. For example, a recent animal study by Kujawa and Liberman[7] demonstrated that damage caused by noise exposure early in life made mice more susceptible to age-related hearing loss.

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The current paper begins with a brief description of human hearing mechanisms, types of hearing loss, and the epidemiology of NIHL, then, primarily discusses the nature of NIHL, including histopathology, signs and symptoms, audiometric profiles, and the impact of hearing loss. This paper concludes with recommendations for prevention of NIHL and available training courses for practicing physicians.

Hearing mechanisms

The human auditory system consists of three main peripheral auditory components (outer ear, middle ear, inner ear) and acoustic nerve (8th cranial nerve). The outer ear gathers sound energy and transmits it to the middle ear through the ear canal and the eardrum (or tympanic membrane). The eardrum vibrates from the incoming sound energy and transmits these vibrations to the inner ear, through the tiny bones in the middle ear, known as the ossicles. The middle ear is filled with air and connects to the throat via the eustachian tube that is instrumental in equalizing pressure on either side of the eardrum. The inner ear has two parts, the vestibular system and the cochlea. The vestibular system is an organ of balance rather than of hearing and is primarily responsible for detecting movement of the head and, to a lesser extent, position in space. Vertigo is a main symptom of the damage to the vestibular system.[8]

The cochlea, shaped like a snail, contains thousands of delicate hair cells (auditory sensory cells) in the organ of Corti. There are two types of hair cells, called inner and outer hair cells. When the sound waves enter the inner ear from the middle ear, the outer hair cells help amplify sound vibrations. The inner hair cells convert these vibrations into electrical signals and send the signals to the brain through the auditory nerve. The brain, then, translates the signals into sound that we recognize and understand. More description on the anatomy and physiology of the auditory system is presented in the paper in this volume by Baiduc et al.

The hair cells of the organ of Corti can be damaged by various factors including aging, loud noise, ototoxic chemicals (solvents, asphyxiants), and ototoxic medications (aminoglycoside antibiotics, Loop diuretics, cisplatin, etc.). More elaborate information on hearing loss related to ototoxic chemicals and medication are presented in the paper in this volume written by Campo et al. Among these, exposure to loud noise is the most common cause of irreversible damage to the hair cells, resulting in sensorineural hearing loss.[8]

Types of hearing loss

The human ear and its neurological connections to the brain represent a complex and sensitive hearing mechanism that is vulnerable to damage by different illnesses, injuries, and toxic exposures.[9] There are two main types of hearing loss: conductive and sensorineural hearing loss. Conductive hearing loss affects the outer or middle ear that includes the pinna, ear canal, eardrum, and the cavity behind the eardrum. There are various etiologies of conductive hearing loss, with the most common including cerumen impaction, middle ear infections such as otitis media, and tympanic membrane perforations. Conductive hearing losses are often temporary or correctable through increasingly sophisticated surgical techniques or medications as is the case with middle ear infections (otitis media).

Sensorineural hearing loss affects the inner ear (sensory) or the auditory nerve (neural) that connects the inner ear to the origin of the nerve in the brain. In current clinical practice, sensory and neural hearing losses are not differentiated regularly and the presence of either is diagnosed as a sensorineural hearing loss. This is mainly due to limitations in the diagnostic techniques used historically to differentiate between these two causes of hearing loss. As techniques for assessing hearing loss are improving, differentiating the source of the loss is becoming more refined, thereby making determination of either sensory or neural loss possible.[9] Sensory and neural loss can occur in isolation or be concurrent. Either or both can also co-occur with a conductive component, caused by a pathology-induced reduction in transmission of the sound energy through the outer and middle ears into the inner ear. A hearing loss is classified as a mixed loss when two or more (conductive, sensory, neural) stages of hearing are simultaneously affected.

Epidemiology of NIHL

Noise is one of the most important occupational and environmental health hazards. Exposure to loud noise causes irreversible auditory damage resulting in sensorineural hearing loss.[1] Approximately one-third of all hearing loss cases can be attributed to noise exposure, and occupational noise exposure is the most common cause of NIHL.[1] In the United States, approximately 10% (22 million) of the adults between 20 and 69 years old have permanent hearing loss due to exposure to loud noise at work or during leisure activities.[10]

NIHL is the most common occupational disease in the U.S. and the second most self-reported occupational illness or injury.[5] Jobs involving exposure to loud noise may include mining, tunneling, quarrying (detonations and drilling), heavy engineering (iron casting, forging press, etc.), operation of machinery driven by powerful combustion engines (trucks, construction vehicles, etc.), operation of textile machines, and testing of engines.[11] Industries with high numbers of exposed workers include agriculture, mining, construction, manufacturing, utilities, transportation, and the military.[5] High-powered motorized equipment, air-powered tools, and striking, drilling, and digging machines are examples of noise exposure. Auditory disabilities (hearing loss and tinnitus) are not restricted to the civilian workforce, as they remain the most prevalent service-compensated injuries among military personnel. In the fiscal year 2010, the Department of Veterans Affair (VA) spent over $1.2 billion to compensate more than 1.4 million veterans on the basis of service-connected auditory disabilities (hearing loss and tinnitus). Thus, NIHL is a significant public health problem for the general population and the workforce.

Histopathology of NIHL

Exposure to loud noise can result in temporary threshold shifts (TTS) and/or permanent threshold shifts (PTS). Moderate exposure in a short time period may initially cause TTS. Hearing loss after a TTS may fully recover within 24–48 h.[12] But this common scientific understanding (possible full recovery from TTS without lasting consequences) has been challenged by the study results on mice that showed completely reversible TTS may increase nerve degeneration and accelerate age-related hearing loss in later life.[13] A possible late-life consequence of neural losses following even a TTS is a particularly important message to deliver to young children and young adults who expose themselves to various recreational noises such as loud computer games or portable music players. Hearing loss after a PTS is irreversible. NIHL in the paper refers to PTS. NIHL differs from occupational acoustic trauma, a sudden hearing loss from single exposure to a very short impulse noise such as gun shot or explosion.[1,6]

Over time, noise exposure leads to damage and loss of the hair cells in the organ of Corti, which is contained in a spiral-shaped structure called the cochlea. These sensory hair cells and surrounding structures are vibrated by incoming acoustic signals and then convert this mechanical vibration into electrical events in the form of firings of the eighth cranial nerve fibers.[9] Chronic exposure to intense noise (sound level above 85 dBA*) initially damages the outer hair cells, which are responsible for high-frequency sounds (3–6 kHz range). (*To gauge how loud 85 dB is, please check the "*Noise Meter*" in the NIOSH website, 〈http://www.cdc.gov/niosh/topics/noise/noisemeter.html〉. There are examples.)

Over time, continued exposure to excessive noise may lead to impaired transmission of both low-and high-frequency sounds to the brain.[6] As the intensity of noise and length of exposure increases, damage in the sensory organ also increases and eventually becomes irreversible. Specifically, cochlear blood flow may be impaired, hair cells become fused into giant cilia or disappear, hair cells and supporting structures disintegrate, and ultimately even the nerve fibers that innervated the hair cells disappear. With degeneration of the cochlear nerve fibers, there is corresponding degeneration within the central nervous system.[1,9] Exposure to loud noise rarely causes damage to the outer or middle ear (conductive loss). Thus, individuals with sensorineural hearing losses, including NIHL, generally have normal-appearing eardrums and middle ear function.[14]

Signs and symptoms of NIHL

Symptoms of possible NIHL include transient tinnitus (ringing or buzzing in the ear), a feeling that the ears are plugged up, or speech or other sounds muffled after exposure to loud noise. Individuals with NIHL often notice difficulty understanding conversation, particularly in unfavorable listening conditions. For example, over 60% of the operating engineers (workers who operate heavy construction equipment) working in the construction industry reported that they had trouble understanding speech in situations with background noise.[15]

Any level of NIHL may muffle high-frequency sounds, such as whistles or buzzers, and may result in difficulty discriminating speech consonant sounds, such as those in the words "fish" and "fist", particularly in environments with background noise, many different voices, or room reverberation.[16] Individuals with NIHL are likely to have more difficulty than expected in ideal face-to-face communication situations.[17] As described earlier, NIHL is inner ear damage, thus it lacks overt symptoms such as pain, bleeding, or easily noticeable deformity. Individuals with NIHL hardly notice their hearing problem until their communication is noticeably compromised.[1,6]

Audiometric characteristics

Insidious sensory damage by noise generally occurs first to hair cells associated with the perception of frequencies above those most important for speech discrimination. In fact, audiometric profiles in NIHL characteristically show a sharp depression at high frequencies between 3 and 6 kHz while the primary speech frequencies (0.5–2 kHz) are normal.[6,9] NIHL preferentially affects the higher frequencies, with hearing loss beginning typically around 4 kHz or 6 kHz, creating a V-shape dip or notch because these two audiometric frequencies are most often affected by noise (see Fig. 1). Historically, this characteristic V-dip or notch was also

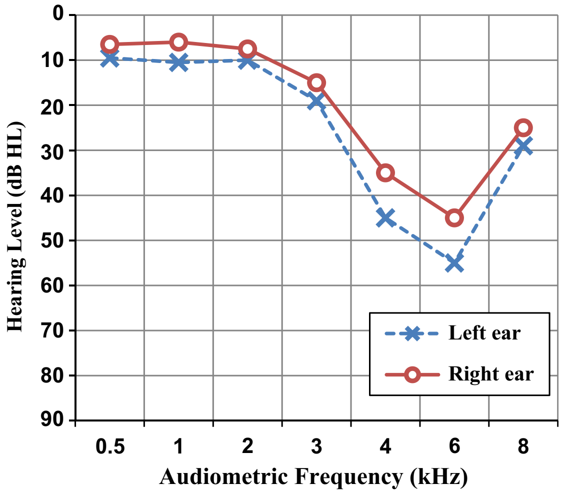

Fig. 1. Typical audiometric pattern of NIHL. (Color version of the figure is available online.)

referred to as the "boilermaker's notch" or "aviator's notch"[18] because it was demonstrated in the cases of hearing loss associated with those specific occupations.

Studies looking at workers exposed to noise have demonstrated a V-shape notch at 4 kHz or 6 kHz as the principle audiometric feature of NIH and the prevalence of hearing loss at these noise-sensitive frequencies far exceeds hearing loss at lower frequencies that are critical to the ability to understand speech.[1,6,15] Hence, this explains why NIHL may be hardly noticed in earlier stages.[1,6] The characteristic V-shape dip or notch at 4 kHz or 6 kHz may be used as an indication of an individual's susceptibility to the effects of noise and of the likelihood that hearing loss will progress to lower frequencies.

As higher frequency hearing loss progresses, the deterioration of hearing loss at lower frequencies follows.[1,6,15] Therefore, it takes longer for lower frequencies (0.5–2 kHz) to be affected by noise than higher frequencies (3–6 kHz). With continued exposure to noise for a period of years, damage will spread both to higher and to lower frequencies, so that the notch will gradually flatten. In advanced cases of NIHL, the audiogram begins to slope downwards at frequencies as low as 0.5 kHz. A V-shaped notch at 4 kHz or 6 kHz, a typical audiometric characteristic of NIHL, may not present for workers who have been exposed to loud noise for many years without proper protection.[17] A case of severe NIHL with disappearance of the notch may eventually become indistinguishable from hearing loss produced by many other causes, such as age-related hearing loss (presbycusis) in which hearing gradually deteriorates at higher frequencies. The presence or absence of NIHL, therefore, cannot be established on the basis of audiometric shape.[1,9] With pure-tone audiometry, the gold standard method of inferring NIHL, complete assessment of NIHL should also include measures of speech understanding and middle ear status.[1] Various auditory tests are described in the paper written by Baiduc et al.

Audiometric patterns in NIHL are usually bilateral and symmetrical.[1,6,9] However, some asymmetry is not unusual. The loss may be predominantly unilateral due to the position of the head during work, especially when the noise is highly pulsating in nature.[11] NIHL, for reasons that are still not yet clearly identified, usually manifests first and rapidly in the left ear.[19,20] Several studies reported poorer hearing in the left ear.[21–23] A more recent study[15] looking at operating engineers in a Midwestern state also found that hearing in the left ear was significantly worse than that of the right ear. According to Hong,[15] there are several plausible explanations for why operating engineers' hearing was significantly worse in the left ear than the right. First, poorer hearing in the left ear may reflect operating engineers' unique directional noise exposure from operating heavy construction equipment. Most operating engineers look over their right shoulder during operation of heavy equipment, and thus their left ear is more exposed to the noise generated by the engine of the heavy equipment that they operate. Also, some workers operate the equipment with the window open, particularly during the hot summer, because many of the machines do not have air conditioning. This phenomenon was also shown in an earlier study with farmers who presumably operate heavy farming equipment such as tractors.[21] Hearing loss seen among hunters or rifle shooters is also typically asymmetrical. Hearing in the ear closest to the barrel tends to be worse because it is closest to the explosion and the other ear is protected by the head shadow.[9] Since the majority of individuals are right-handed, the muzzle blast from a rifle or shotgun reaches the left ear at a higher level than the somewhat protected right ear. Due to the same reason, using firearms, chain saws, and other portable power tools also tends to expose the left ear more directly to the source of noise.[21]

Impact of hearing loss

Although it is not a life-threatening health issue, hearing loss has a profound impact on an individuals' quality of life, primarily through the social handicap resulting from communication interference and various adverse outcomes such as depression, fear, embarrassment, loss of self-esteem, friction in relationships, and stigma.[1] These impacting factors cannot be estimated in concrete measures. The compensation cost for auditory impairment among workers has been consistently increasing. In 2008, 12.2% of the work-related injuries and diseases were attributed to NIHL, with a monetary impact of an estimated $242.4 million annually.[12] There are no valid comprehensive epidemiological data covering the total population.[24]

The inability to hear can be a significant threat to worker's safety and health. Studies have reported hearing loss as a risk factor for occupational injuries among various working populations.[25–28] Morata et al.[29] reported that workers, supervisors, and hearing conservation administrators recognize that worker's safety may be compromised when co-workers have a hearing loss that impacts their ability to communicate and hear important environmental sounds.

Individuals with NIHL may also experience decreased ability in sound localization, which is the ability to gauge the direction and distance of a sound.[30] Impaired ability to localize sounds is of critical importance for certain groups of workers like firefighters and other public safety workers, who rely on hearing during emergency circumstances and for essential tasks such as search and rescue. For certain working populations such as firefighters who require good hearing to perform safe and effective jobs, significant hearing loss can be a career-ending disability and has public safety implications as well.[31] Hearing loss affects not only those individuals who have lost their hearing, but also their co-workers, family members, and society as a whole.[1]

Prevention of NIHL: Hearing conservation program

As described earlier, sensorineural hearing loss due to noise exposure is an irreversible condition with no effective treatment currently possible because hair cells, once damaged, do not regenerate. Fortunately, NIHL is largely preventable.[6] Early detection of such hearing loss through periodic audiometric tests may assist in prevention of further loss, and recognition of existing loss is important for educational and medico-legal purposes. The Occupational Safety and Health Administration (OSHA) recognized that an annual audiometric test is essential for an effective hearing conservation program.[32]

Considering its serious impact on workers' quality of life, NIHL should be prevented with an effective occupational hearing conservation program. OSHA (29 CFR 1910.95) mandates that employers provide a hearing conservation program for all employees who are exposed to noise at or above an 8-h time-weighted average of 85 dB measured on the A scale.[32] This OSHA required occupational hearing conservation program must incorporate five factors: (1) periodic noise exposure monitoring, (2) engineering and administrative controls, (3) personal hearing protection, (4) audiometric evaluations and follow-up activities, and (5) employee/management education and training.[32] However, this requirement is primarily for manufacturing sectors and currently does not apply to many individuals in various industries such as fire services, construction, and agriculture.

The best way to prevent NIHL is to block or reduce noise emission from industrial machinery or noisy equipment through engineering controls; however, these controls are often impractical, costly, or scientifically impossible to fully achieve. Under the occupational noise standard of the OSHA (29 CFR 1910.95), if engineering and administrative controls do not reduce the noise below 90 dB time-weighted average, every worker in the workplace must consistently use personal hearing protection devices (HPDs) such as ear plugs or ear muffs to protect their hearing.

Research has demonstrated that use of personal HPDs has been effective in preventing NIHL.[15,33,34] In order to fully prevent NIHL, workers must consistently use HPDs when noise levels are high; however research shows that workers do not consistently wear them.[24,35–38] Therefore, it is important to develop and implement effective intervention programs to promote the workers' use of personal HPDs.

What do clinicians need to do?

As stated earlier, individuals cannot detect their own early NIHL. Thus, it is important to educate those exposed to loud noise about hearing loss and to encourage them to have hearing tests on a regular basis. Clinicians have a responsibility to teach their clients who are exposed to loud noise (occupationally and/or recreationally) about the characteristics of NIHL, such as insidious onset, gradual development over several years, and difficulty noticing the presence and severity of hearing loss. More importantly, clinicians should encourage individuals who are at risk for NIHL to use personal HPDs whenever they are exposed to noise.

Clinicians may also engage as partners with occupational hearing conservationists in communities of practice to promote hearing health. NIHL is a public health problem requiring involvement by multiple stakeholders for solutions. Clinicians are key to providing preventive solutions to individuals during clinical encounters. Clinicians can also be valued partners in broader community-based interventions to prevent NIHL. One way to become involved is continuing professional education in occupational hearing conservation, as described in the next paragraph.

The Council for Accreditation in Occupational Hearing Conservation (CAOHC) is a non-profit organization whose mission is to promote the conservation of hearing by enhancing the quality of occupational hearing conservation programs. CAOHC offers a certificate-based one-day workshop to prepare physicians and audiologists for the role of Professional Supervisor of the Audiometric Monitoring Program (PS). Candidates who successfully complete a standardized exam earn certification as a Professional Supervisor of the Audiometric Component of the Hearing Conservation Program (CPS/A). Certification is valid for five years. Recertification is available by successfully completing the online Professional Supervisor (CPS/A) exam.

According to OSHAs Hearing Conservation Amendment

> a technician who performs audiometric tests…………..must be responsible to an audiologist, otolaryngologist or physician…(who) shall review problem audiograms….determine whether there is a need for further evaluation……revise audiometric baselines ……(and) supervise and be responsible for the training and competence of the OHC (OSHA, 29 CFR 1910.95).

Consistent with these requirements, CAOHC has developed the PS Scope of Practice.[39] Five PS responsibilities and sample learning objectives from a CAOHC PS workshop are described next.[40]

Establishment and supervision of the audiometric testing program: The PS will understand necessary protocols for audiometric testing and follow-up; identify appropriate test equipment and environment specifications; understand the roles of the PS and the Occupational Hearing Conservationist (OHC); and differentiate between acceptable and invalid audiograms.

Review of problem audiograms: The PS will be able to identify problem audiograms for possible referrals, describe the critical elements of early identification of hearing shift, calculate an age corrected standard threshold shift (STS) and identify conditions for use, identify when baseline revision is necessary and identify regulatory hearing loss recordability criteria.

Determination of work-relatedness: The PS will be able to recognize elements and processes involved in determining work-relatedness and recognize PS responsibilities in determining work-relatedness of hearing loss.

Follow-up of work-related auditory disorder(s): The PS will be able to develop a systematic approach to the differential diagnosis of NIHL, define acoustic trauma and gradual onset NIHL, describe the natural history of NIHL, recognize noise factors which contribute to occupational hearing loss, and apply derating of the hearing protector noise reduction rating (NRR).

Management of the audiometric database: The PS will be able to list key data to capture in the audiometric database, identify early flags for individuals at risk of NIHL and describe reasons for test-test variability.

In summary, the CAOHC professional supervisor course is a comprehensive preparation for the multidimensional expertise involved in effective occupational hearing conservation programs. The PS workshop schedule is available on the CAOHC website at 〈http://www.caohc.org/professional_supervisor/〉.