August 3, 2021 - Volume - Issue

Research Article: PDF Only

Five-Year Longitudinal Cohort Study Determines the Critical Intervals for Periodic Audiometric Testing Based on 5070 Tests of

Metallurgical Workers Exposed and Nonexposed to Noise

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Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and text of this article on the journal's Web site (www.ear-hearing.com).

ACKNOWLEDGMENTS: V.A.R.d.S., A.N.C., and A.C.G. provided substantial contributions to the conception or design of the work. V.A.R.d.S., J.L., and H.F.P. provided acquisition, analysis, and interpretation of the data for the work. A.S.M.D., A.M.C., and C.T.C. drafted the work and revised it critically for important intellectual content, provided final approval of the version to be published, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

The authors have no conflicts of interest to disclose.

Received September 9, 2020; accepted April 20, 2021

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Ear and Hearing: July 1, 2021 - Volume - Issue -
doi: 10.1097/AUD.0000000000001077

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Metrics

Abstract

Objectives:

To compare the progression of 3-, 4-, and 6-kHz thresholds (pure-tone average) over 5 years and determine the most critical period for occupational risk among workers exposed and nonexposed to noise.

Design:

Metallurgical workers were divided into 2 groups: noise-exposed and non–noise-exposed groups. The 6 initial audiometric tests of each worker were analyzed as baseline test and annual tests 1 to 5.

Results:

A total of 845 workers were included, 748 in the noise-exposed group and 97 in the non–noise-exposed group, resulting in 5070 tests analyzed. The nonexposed group showed no significant difference in the mean pure-tone averages between any of the annual tests in either ear. In the exposed group, a significant difference was observed in mean pure-tone averages between baseline and Test1 (p = 0.001 right ear; p = 0.001 left ear), between Test3 and Test4 (p = 0.002 right ear; p = 0.005 left ear), and between Test4 and Test5 (p = 0.003 right ear; p = 0.001 left ear). There was no difference between Test1 and Test2 or between Test2 and Test3 in either ear.

Conclusions:

The progression of pure-tone averages at 3, 4, and 6 kHz differed between workers exposed and nonexposed to noise. Noise-exposed workers had a significant progressive worsening of audiometric thresholds after 3 years of employment. This study identified, in an unprecedented way, two critical periods of noise exposure: in the first year and after the third year of employment in a noisy environment.

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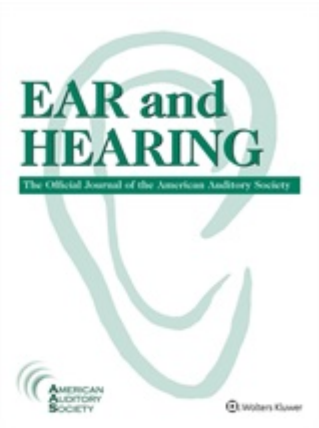

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Five-year longitudinal cohort study determines the critical intervals for periodic audiometric testing based on 5070 tests of metallurgical workers exposed and non-exposed to noise

Abstract

Objectives: To compare the progression of 3-, 4-, and 6-kHz thresholds (pure tone average) over 5 years and determine the most critical period for occupational risk among workers exposed and non-exposed to noise.

Design: Metallurgical workers were divided into 2 groups: noise-exposed and non-noise-exposed groups. The 6 initial audiometric tests of each worker were analyzed as baseline test and annual tests 1 to 5.

Results: A total of 845 workers were included, 748 in the noise-exposed group and 97 in the non-noise-exposed group, resulting in 5070 tests analyzed. The non-exposed group showed no significant difference in the mean pure tone averages between any of the annual tests in either ear. In the exposed group, a significant difference was observed in mean pure tone averages between baseline and Test1 (p=0.001 right ear; p=0.000 left ear), between Test3 and Test4 (p=0.002 right ear; p=0.005 left ear), and between Test4 and Test5 (p=0.003 right ear; p=0.000 left ear). There was no difference between Test1 and Test2 or between Test2 and Test3 in either ear.

Conclusion: The progression of pure tone averages at 3, 4, and 6 kHz differed between workers exposed and non-exposed to noise. Noise-exposed workers had a significant progressive worsening of audiometric thresholds after 3 years of employment. This study identified, in an unprecedented way, two critical periods of noise exposure: in the first year and after the third year of employment in a noisy environment.

Funding: None.

Conflict of Interest: The authors have no conflicts of interest to disclose.

Introduction

Although the incidence of noise-induced hearing loss (NIHL) grew rapidly during and after the industrial revolution, it was not until shortly after the end of World War II that serious efforts were made to evaluate and reduce the risk of NIHL (Kerr et al., 2017). During the 1950s and 1960s, several organizations issued recommended standards intended to limit workers' exposure to hazardous noise levels (Thurston, 2013).

NIHL is irreversible (Le et al., 2017). Hearing is initially affected at the frequencies of 3, 4, and 6 kHz, extending to the frequencies of 0.25, 0.5, 1, 2, and 8 kHz later. NIHL can cause tinnitus, difficulty understanding speech, and hyperacusis, in addition to vestibular disorders such as imbalance, vertigo, and spontaneous nystagmus (Hinchcliffe et al., 1992; Le et al., 2017; Raghunath et al., 2012; Wang & Young, 2007).

NIHL is a complex disease that results from the interaction of genetic and environmental factors and affects individuals differently by multiple mechanisms that manifest differently at various stages (Le et al., 2017). Overexposure to sound can damage the auditory system at multiple anatomic levels. Noise trauma can result in two types of injury to the inner ear, depending on the intensity and duration of the exposure: either transient attenuation of hearing acuity, also known as temporary threshold shift, or permanent threshold shift. Hearing generally recovers within 24 to 48 hours after temporary threshold shift. The characteristic pathological feature of NIHL with permanent threshold shift is the loss of hair cells, particularly the prominent loss of outer hair cells at the basal turn, while loss of inner hair cells is limited (Nordmann et al., 2000). The impact of hearing loss in workers exposed to noise might be underestimated, as recent studies have shown evidence for hidden hearing loss and synaptopathy-induced poor speech recognition (Chen et al., 2018).

Workers exposed to noise undergo periodic audiometric testing for early detection of hearing loss. Worsening of auditory acuity in the short term may indicate that hearing conservation measures adopted by the company have been ineffective. The optimal frequency of occupational audiometric tests remains unclear, and the available evidence does not come from population-based studies. However, there is general medical agreement that audiometric testing should be performed annually (Silva et al., 2020).

Few studies have assessed the impact of noise on workers' hearing health since the beginning of noise exposure. A study in Tanzania of iron and steel workers with a mean exposure duration of 5 years (range: 0–24 years) found a higher prevalence of hearing loss in noise-exposed workers (48%) than in controls (31%), and the comparison of hearing thresholds between the two groups for the frequencies of 4 and 6 kHz showed significant differences (Nyarubeli et al., 2019).

The present study aimed to compare the progression of audiometric thresholds at the frequencies of 3, 4, and 6 kHz (pure tone average) and to determine the most critical period for occupational risk in the first 5 years of employment among workers exposed and non-exposed to noise.

Methods

This study was approved by the Institutional Review Board of the University of Campinas (0810.0.146.000-11). Data from audiometric tests performed between January 2003 and January 2019 were obtained from 4 different metallurgy companies in southeastern Brazil. The workers evaluated in this study are from metallurgy companies that manufacture auto parts (engines, shock absorbers, and brakes). We excluded workers who cut steel due to specific noise characteristics and the use of lubricants that may contain ototoxic substances, such as lead and mercury.

The level of noise exposure, measured as the A-weighted equivalent sound level (LAeq), ranged from 85 to 87 dB (mean of 85.61 dB) in noise-exposed workers, according to information provided by the companies. Among non-exposed workers, the LAeq ranged from 74 to 81 dB (mean of 76.8 dB). Workers exposed to vibration or impulsive noises were not included in the study. Noise-exposed workers used 3M™ E-A-R™ Flexible Fit Earplugs, with washable foam. The level of noise attenuation ranges from16 to 20 dB depending on the manufacturer. At each company, upon hiring and every 6 months, workers are trained by occupational health technicians on the correct use of hearing protection devices (HPDs) and the importance of using them correctly. Each company has its own policies for punishing workers who do not use the devices correctly, which may lead to warnings and even dismissal.

Brazil ratified the International Labor Organization Convention 148 on January 14, 1982. In 1978, Brazil enacted Law No. 3214, which is composed of 29 regulatory standards. Each regulatory standard is related to a type of health and safety regulation. Regarding occupational noise, the law establishes a permissible exposure limit of 85 dBA with a 5 dB exchange rate. Continuous exposure levels must be measured using the slow response of a sound level meter. For individuals without hearing protection, exposures above 115 dBA are not permitted. Regulatory standard 6 concerns hearing protection requirements, and regulatory standard 17 establishes acoustic comfort limits for jobs that require mental concentration. Regulatory standard 9, updated in 1994, outlines prevention programs for environmental risks. Noise control measures must be implemented when time-weighted average levels exceed 80 dBA for 8 hours (corresponding to a dose of 50%) (Arenas & Suter, 2014). All 4 companies had implemented hearing conservation programs according to the National Noise and Hearing Conservation Committee guidelines.

Workers aged >40 years at baseline as well as workers with diabetes, hypertension, and autoimmune and infectious diseases were excluded. Presbycusis is the most common sensory deficit in older people, and men are generally more severely affected than women. Although there is a constant decline in hearing acuity with aging, age of onset, progression and severity of age-related hearing impairment show great variation, which is at its largest in the high frequencies and increases with age (Fransen et al., 2003). Comorbidities such as hypertension, diabetes mellitus, autoimmune diseases, infectious diseases, and immunodeficiencies can worsen hearing thresholds regardless of noise exposure (Le et al., 2017). Because these factors could interfere with the analysis of hearing thresholds, these workers were excluded from the study.

Female workers were also excluded from the study. Epidemiologic studies of large populations of unscreened older adults have shown an accelerated decline in hearing sensitivity after the age of 20-30 years in men and after the of age 50 years in women, with the average hearing thresholds of men indicating a sharp increase in hearing loss in the high-frequency range, whereas women's audiograms indicate a more gradual increase. The protective effect of estrogen on the cochlea appears to result from its ability to coordinate and enhance multiple cell survival signaling pathways (Wang & Puel, 2020). Moreover, in the metallurgy industry, women are mostly employed in administrative and human resources departments, and only a few of them work on the production line.

Additional exclusion criteria were incomplete audiometric data, occupational noise exposure before baseline, conductive hearing loss, complaints of tinnitus, any known chronic disease (hypertension, diabetes mellitus, autoimmune diseases, infectious diseases, or immunodeficiencies), and tests performed for any reason other than occupational noise exposure. We also excluded workers whose tests were performed with a time interval of less than 6 months or of more than 16 months.

Metallurgical workers were divided into 2 groups: (1) noise-exposed group: workers exposed to ≥ 85 dB sound pressure level for at least 8 hours/day, who were provided with HPDs (earplugs) by the company as required by law; and (2) non-noise-exposed group: workers exposed to < 85 dB sound pressure level for at least 8 hours/day. The variation in the sound pressure level in each company was not statistically significant.

The audiometric tests were performed in a specialized center. Pure tone audiometry was performed by 6 different speech therapists with significant experience in audiometric testing procedures for occupational noise exposure. Prior to audiometry, all ears were examined to rule out possible external ear canal obstruction or any other pathology affecting the auditory system.

The 6 initial audiometric tests of each worker were analyzed as baseline test and annual tests 1 to 5. Baseline was defined as the worker's first test after being hired but before starting to work. The post-baseline annual tests are referred to as Test1, Test2, Test3, Test4, and Test5.

Two calibrated audiometers, a Madsen Midimate 622 (GN Otometrics, Taastrup, Denmark) and an Interacoustics AD 29 (Interacoustics, Assens, Denmark), were used for the testing procedures. All audiometric tests were performed according to the following parameters: air conduction at frequencies from 0.25 to 8 kHz.

Eligible participants were all male metallurgical workers aged 18 to 40 years who had undergone at least 6 audiometric tests (baseline, Test1, Test2, Test3, Test4, and Test5) with 14 hours of hearing rest prior to each test and who had normal baseline results. Table 1 shows the mean time interval between the audiometric tests.

For each worker, pure tone average was calculated at 3, 4, and 6 kHz in the left and right ears for each test. Because only the 3-, 4-, and 6-kHz frequencies are early affected by noise, they were targeted in this study. The frequencies of 0.25-2 kHz and 8 kHz are only later affected in noise-exposed patients and, therefore, were not considered in the statistical analysis.

The exposed and non-exposed groups were compared at baseline and at annual tests 1 to 5 with the Mann-Whitney U test. Results were considered statistically significant at $p<0.05$. Data were analyzed using R software (http://www.R-project.org).

Results

A total of 7393 workers had a baseline test recorded in the companies' database. Of these, 5759 were exposed to noise and 1634 were not exposed to noise. Figure 1 shows the flow diagram of selection of workers for the study. None of the workers evaluated had previous occupational noise exposure. A total of 845 workers were included, 748 in the noise-exposed group and 97 in the non-noise-exposed group, resulting in 5070 tests analyzed. Based on the date of baseline testing, mean age was 28.5 years for exposed workers and 29.7 years for non-exposed workers, with no significant difference between the groups (p=0.743).

The frequencies from 0.25 to 8 kHz were evaluated in all workers at each audiometric test, and the results are presented in Table 2 for noise-exposed workers and in Table 3 for non-noise-exposed workers. The variations at each frequency for each ear over time are illustrated in Figure 2 for exposed and non-exposed workers. These results show that the frequencies of 3, 4, and 6 kHz are the most affected by noise in exposed workers over time.

There was no significant difference between the mean pure tone averages at 3, 4, and 6 kHz between exposed and non-exposed workers at baseline (p=0.082 right ear; p=0.065 left ear). Table 4 shows the mean pure tone averages at 3, 4, and 6 kHz at baseline, Test1, Test2, Test3, Test4, and Test5 in the non-exposed and exposed groups.

Table 5 shows the differences in the mean pure tone averages between the tests (effect size). In the non-noise-exposed group, mean pure tone averages varied only slightly between the tests throughout the years, ranging from 0.89 dB (right ear) to 0.75 dB (left ear) after 5 years. In the noise-exposed group, there was a larger variation between Test1–Baseline, Test4–Test3, and Test5–Test4. After 5 years of exposure, hearing shift ranged from 2.93 dB (right ear) to 3.06 dB (left ear).

Table 6 shows a comparison of the mean pure tone averages at 3, 4, and 6 kHz between the different annual audiometric tests. The non-exposed group showed no significant difference between any of the annual tests in either ear. In the exposed group, a significant difference was observed in mean pure tone averages between baseline and Test1, between Test3 and Test4, and between Test4 and Test5 for the right and left ears. There was no significant difference between Test1 and Test2 or between Test2 and Test3 in either ear. Comparisons at each frequency evaluated from 0.25 to 8 kHz are provided as supplementary material (Tables S1 and S2).

Figure 3 shows the progression of pure tone averages over time. There was an increase in the hearing threshold over time, more noticeable in the exposed group from baseline to Test1 and after Test3.

Table 7 shows the percentage of noise-exposed workers who developed a standard threshold shift (STS) compared to baseline, which was detected only after Test4, according to the Occupational Health and Safety Administration (OSHA), National

Institute for Occupational Safety and Health (NIOSH), and Brazilian criteria. Non-exposed workers did not develop an STS, according to these criteria.

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Discussion

Periodic audiometric testing can identify hearing loss at a time when early detection and preventive interventions are possible. Testing also provides an opportunity to educate workers on the lasting effects of noise exposure and to increase awareness of noise hazards present in daily activities (Leshchinsky, 2018). In the current study, workers exposed to noise showed a slowly progressive worsening of audiometric thresholds, especially after 3 years of employment.

Some factors may have contributed to the difference in sample size between the exposed and non-exposed groups. Most of the companies’ employees work on the production line, where most workers are exposed to noise, but, at the same time, strict noise control measures are in place to ensure periodic audiometric testing of these workers due to an increased risk of hearing impairment. Administrative and human resources staff, however, are subject to less strict regulation on periodic audiometric testing; therefore, we had to exclude staff members who did not undergo audiometric testing within an appropriate time frame for the study.

Each company in this study has its own policy to control sound exposure level, although all of them follow the government regulations that require the use of hearing protection in noisy environments. Measures to reduce noise levels and use of hearing protection are essential to reduce the damage caused by noise, but none of the companies could provide statistical data to confirm proper use of hearing protection by all workers exposed to noise.

Hearing conservation measures include engineering solutions to minimize noise emission and to limit the duration of noise exposure in the workplace, in addition to enforcing the use of HPDs (Rawool, 2012). Worsening of workers' audiometric thresholds over time may indicate that the measures adopted by the company are not effective or not being followed (Frederiksen et al., 2017). Unlike the workers exposed to noise, the non-noise-exposed workers showed no significant differences in their annual audiograms, with an effect size between baseline and Test5 of 0.89 dB in the right ear and 0.75 dB in the left ear. The administrative and human resources staff of the metallurgy companies were exposed to <85 dB for 8 hours/day; therefore, annual audiometric testing may be unnecessary in the first 5 years of employment in this group.

Measures to reduce noise levels and use of hearing protection were unable to avoid hearing shifts caused by noise in the present study. Statistical analysis showed significant differences in workers exposed to noise at the 3-, 4-, and 6-kHz frequencies. A significant worsening of audiometric thresholds was observed between baseline and Test1, Test3 and Test4, and Test4 and Test5 (Table 6). Perhaps the measures implemented in the companies are not sufficient to fully protect the noise-exposed workers. Of note, despite the significant difference in the first year of exposure, hearing loss showed no further signs of deterioration in the second and third years of exposure, with an effect size numerically similar to that of non-exposed workers (Table 5). A possible explanation is that self-defense mechanisms similar to those triggered by small doses of ototoxic substances may have been activated after the early period of noise exposure, which reduced the progressive changes in hearing thresholds. This protective effect may be similar to that of a non-ototoxic dose of amikacin administered before the ototoxic dose of the same antibiotic (Oliveira et al., 2004). However, after the third year of exposure, this mechanism was no longer sufficient to prevent the worsening of thresholds (Figure 3).

The pathophysiology of NIHL is complex. Multiple, potentially interacting types of noise-induced changes can occur in the auditory system without significantly compromising hearing thresholds (Verhulst et al., 2016). When compared numerically, the exposed group differed only slightly from the non-exposed group at 5 years in audiometric worsening, which was 3.29 times higher in the right ear and 4.08 times higher in the left ear. In this respect, auditory brainstem response testing could have detected the early stages of NIHL. This highlights the need for a comprehensive test battery, not only standard audiometry; however, we understand that it may be outside the scope of what is considered practical in the clinical assessment of hearing loss.

Despite the significant differences observed over the years, hearing is considered to have worsened if thresholds increase by more than 10 dB between tests based on the mean results for 3 consecutive frequencies, such as 3, 4, and 6 kHz. In the present study, although audiometry could identify increases in thresholds every year or even after 5 years of noise exposure, the difference was on average less than 1 dB between subsequent tests, and less than 5 dB at the end of 5 years (Table 5). This small increase in the hearing threshold was only detected when calculating the averages among workers. Limitations inherent to audiometric testing do not allow the examiner to detect increases of less than 5 dB in thresholds at the individual level. Exposure to noise can cause injury at the synapse between the inner hair cells and the auditory neurons, which is not reflected on audiograms. This synaptic injury has been suggested to be related to hidden hearing loss and the degradation of speech intelligibility among other noise in the presence of normal audiometric thresholds (Chen et al., 2020). The present study shows that noise-exposed workers have a more accelerated, progressive rhythm of worsening of audiometric

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thresholds than non-noise-exposed workers, but this hearing shift is not detectable at the individual level.

The OSHA considers an STS to occur when there is an average threshold worsening of 10 dB or more for the frequencies of 2, 3, and 4 kHz. The NIOSH defines an STS as a change of 15 dB or more at any frequency between 0.5 and 6 kHz (Rawool, 2012). The Brazilian regulatory agency considers an STS to occur when there is a difference between the arithmetic hearing threshold averages of 10 dB HL or more for the frequencies of 3, 4, and 6 kHz or an average threshold worsening of 15 dB HL or more in at least one of the frequencies of 3, 4, or 6 kHz (Arenas & Suter, 2014). As shown in Table 7, the noise-exposed workers identified by the Brazilian criteria to have developed an STS were the same workers identified by the NIOSH criteria. None of these workers reached the threshold of 25 dB HL at any of the frequencies analyzed. The OSHA STS criteria are the most commonly used criteria worldwide (Rawool, 2012). However, in the present study, we would have failed to detect 3 workers who developed an STS at Test4 and 5 workers at Test5 if we had applied only the OSHA criteria for STS, compared to the NIOSH and Brazilian criteria. An STS rate of 3% or less in noise-exposed workers indicates an effective hearing conservation program (Rawool, 2012). Thus, as the highest STS rate in our study was 1.47%, we may assume that the companies have an effective hearing conservation program.

Over the first 4 to 6 years of hearing conservation programs that are classified as acceptable, the mean pure tone averages at 3, 4, and 6 kHz often improve compared to baseline because workers learn the task of responding to pure tones (learning curve) (Royster & Royster, 1986; Royster et al., 1980). In the present study, this effect was not observed in either group. There was an increase in pure tone averages over time even in workers not exposed to noise, although the difference was not statistically significant.

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Consistent with a study of iron and steel workers conducted in Tanzania (Nyarubeli et al., 2019), with a mean exposure duration of 5 years, which found a higher prevalence of hearing loss in noise-exposed workers than in controls, especially for the frequencies of 4 and 6 kHz, our study also showed an increase in hearing thresholds over time, which was statistically significant in noise-exposed workers.

We identified critical periods of occupational noise exposure in the population under study. Audiometric thresholds tended to worsen in the first year and after the third year of employment in workers exposed to noise. These thresholds seem to stabilize between the second year and third year, when there is an increase in hearing loss until the fifth year of employment. Therefore, we suggest that test results should be carefully monitored after the third year of employment even if audiometric testing cannot be performed annually or the values have not exceeded 10 dB, as hearing shifts less than 10 dB may also have an impact on hearing health.

Our study has some limitations. For the reasons explained earlier, we did not assess the impact of noise on female workers. Also, after applying the exclusion and inclusion criteria, there were only 13 women in the exposed group to analyze (vs 748 men), whereas the non-noise-exposed group would have 394 women (vs 97 men). Excluding workers older than 40 years, as well as those with chronic diseases and using ototoxic medications that could lead to hearing impairment, was important to reduce possible bias. However, this prevented us from drawing any conclusions concerning older individuals, who could be more impacted by NIHL. We also had to exclude workers who work in machining processes (cutting steel) because, although they are exposed to more intense noise (impactive noises), they use specific HPDs that are different from those used by the other workers, work fewer hours, and use lubricants that contain ototoxic heavy metals, which would make it difficult to properly analyze the data. Audiometric thresholds may vary slightly from one test to the subsequent test due to the experience and motivation of the examiner and patient (Schlauch & Carney, 2012). When audiometric testing is applied to occupational screening, this variability increases even more due to several sources of systematic and random errors (Hétu, 1979). The use of audiometric booths with adequate sound insulation, calibrated instruments and experienced speech therapists can reduce these biases. The fact that 6 different speech therapists performed the audiometric tests may have reduced the strength of our data. However, it is almost impossible to ensure that a single person will perform all the tests over a long period of time.

Noise control is the most effective approach to hearing conservation. For the implementation of engineering noise controls, noise control engineers may serve as the key personnel. However, collaboration of several professionals, including the workers, is likely to produce the most effective noise control measures (Rawool, 2012). It is difficult to fully control the proper use of HPDs in the companies. Although workers are periodically trained on the importance and correct use of HPDs (and even punished in case of inappropriate use), environmental conditions such as excessive heat and humidity may cause discomfort and communication during tasks may be limited with the use of earplugs. It is therefore important to strike a balance between noise attenuation and comfort to maximize the effectiveness of HPDs (Arezes & Miguel, 2002). HPDs would probably be better accepted if they were tailored to the individual worker.

Difficulty in controlling recreational noise exposure outside the workplace is another factor to be considered. The free field equivalent SPLs from personal stereo systems can range from 91 to 121 dBA at the highest volume control settings, and some peaks in music samples can be as high as 139 dB SPL (Fligor & Cox, 2004). We have no reason to believe that the noise-exposed metallurgical workers included in the present study were more exposed to noise in home or recreational settings, especially because they were not involved in shooting practices, than the non-noise-exposed controls. In addition, it is almost impossible to monitor all workers in their home or recreational settings.

This study is important because it is one of the few to assess NIHL since the beginning of occupational noise exposure in a group of young workers with noise exposure below 90 dB HL and with the use of HPDs. A strength of this study is the elimination of biases such as exposure to ototoxic substances in the workplace and the use of medications that could cause hearing loss. This study showed that hearing shifts can occur more slowly at the early period of noise exposure, with a slower progression of auditory sensitivity in the second and third years, when it accelerates again. If confirmed by other studies, this information can be a new paradigm for the audiometric monitoring of all workers exposed to noise.

Conclusion

The progression of pure tone averages at 3, 4, and 6 kHz differed between metallurgical workers exposed and non-exposed to noise. Non-noise-exposed workers had no significant differences in annual testing over a 5-year period. Noise-exposed workers had a significant progressive worsening of audiometric thresholds after 3 years of employment. Two critical periods of noise exposure were identified: in the first year and after the third year of employment.

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