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The Use of the Kurtosis-adjusted Cumulative Noise Exposure Metric in Evaluating the Hearing Loss Risk for Complex Noise

Hong-wei Xie[1], **Wei Qiu**[2], **Nicholas J. Heyer**[3], **Mei-bian Zhang**[1], **Peng Zhang**[4], **Yi-ming Zhao**[5], and **Roger P. Hamernik**[2]

[1]Center for Disease Control and Prevention of Zhejiang, Hangzhou, P.R.China

[2]Auditory Research Laboratories, State University of New York at Plattsburgh, Plattsburgh, NY 12901 USA

[3]Battelle Centers for Public Health Research and Evaluation, Seattle, Washington, USA

[4]Center for Disease Control and Prevention of Huzhou, Huzhou, P.R.China

[5]Center for Clinical Epidemiological Research, Peking University Third Hospital, Beijing 100083, P.R.China

Abstract

Objective—To test a kurtosis-adjusted cumulative noise exposure (CNE) metric for use in evaluating the risk of hearing loss among workers exposed to industrial noises. Specifically: to evaluate if the kurtosis-adjusted CNE (1) provides a better association with observed industrial noise-induced hearing loss; (2) provides a single metric applicable to both complex (non-Gaussian) and continuous or steady-state (Gaussian) noise exposures for predicting noise induced hearing loss (dose-response curves).

Design—Audiometric and noise exposure data were acquired on a population of screened workers (N = 341) from two steel manufacturing plants located in Zhejiang province, and a textile manufacturing plant located in Henan province, China. All the subjects from the two steel manufacturing plants (N=178) were exposed to complex noise while the subjects from textile manufacturing plant (N=163) were exposed to a Gaussian (G) continuous noise. Each subject was given an otologic examination to determine their pure tone hearing threshold levels (HTL); and had their personal 8-hour equivalent A-weighted noise exposure (L_{Aeq}) and full shift noise kurtosis statistic (which is sensitive to the peaks and temporal characteristics of noise exposures) measured. For each subject an unadjusted and kurtosis-adjusted cumulative noise exposure (CNE) index for the years worked was created. Multiple linear regression analysis controlling for age was used to determine the relationship between CNE (unadjusted and kurtosis-adjusted) and the mean HTL at 3, 4 and 6 kHz (HTL_{346}) among the complex noise exposed group.

In addition, each subjects' HTLs from 0.5 - 8.0 kHz were age and gender adjusted using ANNEX A (ISO-1999) to determine whether they had adjusted high frequency noise induced hearing loss (AHFNIHL), defined as an adjusted HTL shift of 30 dB or greater at 3.0, 4.0 or 6.0 kHz in either

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Corresponding Author: Wei Qiu, Ph.D, Auditory Research Laboratories, State University of New York at Plattsburgh, 101 Broad Street, Plattsburgh, NY 12901, qiuw@plattsburgh.edu, Telephone: 518-564-7706.

ear. Dose-response curves for AHFNIHL were developed separately for workers exposed to G and non-G noise using both unadjusted and adjusted CNE as the exposure matric.

Results—Multiple linear regression analysis among complex exposed workers demonstrated that the correlation between $HTL_{3,4,6}$ and CNE controlling for age was improved when using the kurtosis-adjusted CNE compared to the unadjusted CNE (R^2=0.386 vs. 0.350), and that noise accounted for a greater proportion of hearing loss. In addition, while dose-response curves for AHFNIHL were distinctly different when using unadjusted CNE, they overlapped when using the kurtosis-adjusted CNE.

Conclusions—For the same exposure level, the prevalence of NIHL is greater in workers exposed to complex noise environments than for workers exposed to a continuous noise. Kurtosis adjustment of CNE both improved the correlation with NIHL and provides a single metric for dose response effects across different types of noise. The kurtosis-adjusted CNE may be a reasonable candidate for use in NIHL risk assessment across a wide variety of noise environments.

Introduction

Current international standards for exposure to noise (ISO-1999, 2013) rely solely on an energy metric. The equal-energy hypothesis (EEH), which has been used to establish and implement noise guidelines, assumes that the cochlear impact of noise exposure is proportional to the duration of exposure multiplied by the energy intensity of the exposure. Thus, equivalent effects on hearing would be expected for a 3-dB increase or decrease in exposure intensity accompanied with a halving or doubling of the exposure duration respectively. This approach is generally considered appropriate for continuous, or steady-state (Gaussian, G) noise but not for complex noise (Ahroon et al., 1993). A complex noise is a non-Gaussian (non-G) noise consisting of a G background noise that is punctuated by a temporally complex series of randomly occurring high-level noise transients. These transients can be brief high-level noise bursts or impacts. While some researchers have argued for the application of the EEH to complex noise environments (Atherley and Martin, 1971; Guberin, et al., 1971; Atherley, 1973), this approach has been contradicted by both laboratory studies (Dunn et al., 1991; Hamernik et al., 2001; Hamernik et al., 2003; Qiu et al., 2006; Qiu, et al., 2007, Davis et al., 2009) and epidemiological studies (Sulkowski et al., 1982; Taylor et al., 1984; Thiery and Meyer-Bisch, 1988). Where the EEH postulates that the risk of noise induced hearing loss (NIHL) for workers is simply a function of the total exposure energy, epidemiologic studies have demonstrated that workers exposed to noise environments containing impact noise transients have an increased prevalence of hearing loss (Taylor et al., 1984; Theiry and Meyer-Bisch, 1988; Zhao et al., 2010). Evidence from noise studies using animal models has also questioned the validity of the ISO-1999 and ANSI S3.44 databases that were constructed using equivalent continuous sound levels (e.g., Dunn et al., 1991; Lei et al., 1994; Lataye and Campo, 1996; Hamernik and Qiu, 2001; Hamernik et al., 2003; Harding and Bohne, 2004; Qiu et al., 2006 and 2007; Davis et al., 2009). These animal studies confirm that the temporal distribution of energy is an important factor in NIHL. Unfortunately, none of these studies have provided sufficient information on the dose-response relation (DRR) between non-G industrial noise and NIHL. Part of the difficulty in trying to establish a DRR is the great diversity of non-G noises found in industry with no commonly accepted method of characterizing them. For example, factors such as the histograms of the peak levels, inter-peak intervals and duration of the embedded transients, in addition to the overall sound pressure level (SPL), spectra and exposure durations need to be taken into account. Neglecting any one of these factors may lead to an unacceptable DRR.

Recent results from animal experiments (Hamernik et al. 2003; Qiu et al. 2006, 2007) have shown that the kurtosis (β) of the amplitude distribution, a statistical metric that is sensitive to the peak and temporal characteristics of a noise, could order the extent of hearing and sensory cell loss from a variety of complex noise exposures. They showed that for a fixed noise energy level and spectra, noise-induced trauma increased as the kurtosis of the noise exposure increased. Thus, there is the possibility that the kurtosis, in combination with the Leq, might be useful in evaluating a broad range of noise environments for hearing conservation purposes.

Preliminary Study

We conducted a preliminary study (Zhao et al, 2010) of workers exposed to mixed noise environments. The study demonstrated that the kurtosis metric could be used to more accurately assess the risk of developing high frequency (3,4 and 6 kHz) NIHL among workers exposed to high level non-G noise. In this study, a new approach to charactering the hazardous effects of complex noise was developed in which an energy based metric [cumulative noise exposure (CNE)] was modified by a kurtosis-related correction term to establish a cumulative noise exposure metric that could be useful for both Gaussian and complex noise environments. This new kurtosis-adjusted CNE was used to predict NIHL among 195 workers exposed to both G noise ($L_{Aeq,8h}$ varied from 95 to 106 dBA, N=163), and a non-G, complex noise ($L_{Aeq,8h}$ = 95 dBA, N=32). Audiometric and noise exposure data were used to create independent dose response relationships for the G and non-G noise exposed workers using both the uncorrected and kurtosis-adjusted CNE. It can be seen in Fig. 1(A) and (B) that by introducing the kurtosis correction, the two dose-response curves were made to overlap, essentially yielding a single metric that produced consistent dose-response noise-induced effect for the two study groups.

While this preliminary study showed promising results, it was based on a small number of workers exposed to complex non-G noise. In the present study, we have collected data on 178 workers with well-documented and diverse exposures to complex noise. Combined with data from the preliminary study, we used these data to (1) further investigate if the kurtosis is useful in predicting industrial NIHL; and (2) verify the prediction method that was developed by Zhao et al. (2010).

Materials and Methods

Subjects—Industrial workers exposed to complex noise were recruited from (A) a steel rolling mill in Hangzhou; and (B) a steel framework manufacturing plant in Huzhou, both in the Zhejiang province of China. Data on workers exposed only to Gaussian noise at (C) a textile mill in Zhengzhou, Henan province of China, had previously been collected by a research team at Peking University Third Hospital using similar criteria and measurement techniques (Zhou, et al, 2010).

Inclusion criteria were the same for subjects from all three industrial settings. All subjects had to satisfy six criteria: (1) a minimum of at least one year employment at their current task; (2) consistently worked within the same job category and worksite (noise exposure area) for their entire employment; (3) no history of genetic or drug-related hearing loss, head wounds or ear diseases; (4) no history of military service or shooting activities; (5) no history of using hearing protection; and (6) no co-exposure to noise and chemicals or heavy metals.

Subjects were introduced to the purpose of and procedures to be followed in this study by an occupational physician, and were asked to sign an informed consent form. The Zhejiang Center for Disease Control and Prevention institutional committee for the protection of human subjects approved the protocol for this study.

Questionnaire Survey—An occupational hygienist at the Zhejiang Center for Disease Control and Prevention administered a questionnaire to each subject in order to collect the following information: general personal information (age, sex, etc.); occupational history (factory, worksite, job description, length of employment, duration of daily noise exposure, and history of hearing protector use); personal life habits (e.g., smoking and alcohol use); and overall health (including history of ear disease and use of ototoxic drugs). An occupational physician entered all information into a database.

Noise data collection

Non-G Noise—Shift-long noise recording files were obtained for each non-G noise exposed subject at the two steel plants using a digital recorder (Kenwood MGR-A7) operating continuously with 16-bit resolution at a 48 kHz sampling rate. The MGR-A7 recorder is a digital audio recorder that can record high-fidelity sound. Operating in the 48 kHz WAV format with an 8GB SD card, the maximum recording period is 11 hours. Tests by the Institute of Acoustics, Chinese Academy of Sciences, show that the Kenwood MGR-A7 with the AWA5610B (Aihua Instruments, China) as the preamplifier has a frequency response from 20 Hz to 20 kHz and an effective dynamic range of 90 dB. The instrument is easily worn by the subject. The recorders were equipped with a ½ inch microphone (Aihua Instruments, AWA14421) fixed on the collar of each subject. The sensitivity of the AWA14421 is -30 dB and the dynamic range is 20-142 dB. Immediately after recording was completed, the data were transferred from the recorder to a computer for subsequent analyses. The recorder was calibrated before and after each sampling period using a sound calibrator (Aihua Instruments, AWA6221B) according to the manufacturer's instructions.

The kurtosis of the recorded noise signal was computed for consecutive 40-s time windows without overlap over the full shift using MATLAB software. The mean kurtosis of these 40-s windows was calculated and used as the kurtosis value for the entire shift.

G Noise—The kurtosis of the recorded noise signal was computed for consecutive 40-s time windows of each 5- minute G noise record. Zhao et al., (2010) described how noise recording files were obtained for each G noise exposed subject at the textile mill.

Physical and Audiometric Evaluation—Each subject was given a general physical and an otologic examination. Pure tone, air conduction hearing threshold levels (HTL) at 0.5, 1.0, 2.0, 3.0, 4.0, 6.0 and 8.0 kHz were measured in each ear by an experienced physician. Testing was conducted in an audiometric booth using an audiometer (Madsen, OB40) calibrated according to the Chinese national standard (GB4854-84). The noise floor of the booth was compliant with ANSI specifications from 125 to 8000 Hz. Audiograms were measured at least 16 hours after the subjects' last occupational noise exposure.

Determination of an Adjusted Noise-Induced Hearing Impairment—An adjusted high frequency noise-induced hearing loss (AHFNIHL) was defined as one or more of the adjusted HTLs, in either ear, at 3.0, 4.0 or 6.0 kHz being equal to or greater than 30 dB. Measured HTL at each frequency were adjusted by subtracting the median age and gender specific HTL from a noise unexposed standard population [ISO -1999, (2013)]. In the ISO standard 1999 (2013) there is one example of database A for a highly screened population (Annex A) and three examples of database B for an unscreened population (Annex B2-B4). Since the worker population in this study was rigorously screened, Annex A was used to calculate the NIPTS in this study.

It was noticed that audiometric asymmetry was common in our occupational NIHL subject pool (here, audiometric asymmetry is defined by a binaural difference in hearing thresholds of 15 dB or more). It showed that 45.8% of workers in non-G group had audiometric asymmetry while 31.9% workers in the G group. If protection of worker's hearing is the objective then it makes sense to use the age and gender adjusted hearing threshold of the worse ear to establish the onset of NIHL.

Cumulative Sound Energy Exposure Assessment—The cumulative noise exposure (CNE), a composite noise exposure index (Earshen, 1986), was used to quantify the noise exposure for each subject. The CNE is defined as:

$$\mathrm{CNE}=10\log\left[\frac{1}{T_{\mathrm{ref}}}\sum_{i=1}^{n}\left(T_i\times 10^{L_{\mathrm{Aeq},8h_i}/10}\right)\right] \quad (1)$$

where $L_{Aeq.8h_i}$ is the equivalent continuous A-weighted noise exposure level in decibels normalized to an 8h working day; occurring over the time interval T_i in years; with a total of n different noise level exposure periods (i.e., years spent working in different noise tasks/ environments); and T_{ref} = 1 year. For all subjects in this study n = 1 (as all workers were restricted to being exposed in only one occupational noise environment) and equation (1) can be reduced to:

$$\mathrm{CNE}=L_{\mathrm{Aeq},8h}+10\log(T) \quad (2)$$

This equation is typically applied to the evaluation of noise environments that require an estimate of the total exposure energy, and is based on the EEH, which requires the application of a 3-dB intensity-time trade off; i.e., the same total exposure energy is maintained when a 3-dB increase or decrease in exposure intensity is accompanied by a halving or doubling of the exposure duration, respectively. However, as indicated in the introduction, there is considerable evidence that complex industrial noise exposures do not conform to the equal energy model.

In order to incorporate the kurtosis metric (β) into the evaluation of non-G noise environments and to unify CNE calculations for epidemiologic data that include both G and complex noise, Zhao et al. (2010) modified equation (2) as shown below:

$$\mathrm{CNE}'=\mathrm{CNE}_{\mathrm{Kurtosis-adjusted}}=L_{\mathrm{Aeq},8h}+\frac{\ln(\beta)+1.9}{\log(2)}\log(T) \quad (3)$$

This form was chosen for calculating the kurtosis-adjusted cumulative noise exposure because G noise has a kurtosis of $\beta = 3$, and the term $[(\ln(\beta) + 1.9)/\log(2)]$ becomes equal to 10. Thus, for G noise the kurtosis-adjusted *CNE* equals the unadjusted *CNE*. It can be seen from Eq. (3) that for a fixed $L_{\mathrm{Aeq},8\mathrm{h}}$, the kurtosis-adjusted CNE will be larger for non-G noise ($\beta > 3$) than for G noise ($\beta = 3$). In fact, using this equation, the kurtosis metric β logarithmically 'tunes' the standard *CNE*.

Data Processing and Statistical Analysis—Data from each subject's questionnaire was separately entered by two study staff into a database using EpiInfo 6.04D software. The duplicated database was then checked for errors and analyzed with SPSS 18 software package. Correlations between HTL and both unadjusted and kurtosis-adjusted CNE were modelled using multiple linear regression analyses. The average HTL at 3, 4 and 6 kHz (HTL_{346}) of the worse ear was the dependent variable, and age and smoking status were introduced as covariates. Logistic regression was applied to generate and compare dose-response curves for AHFNIHL using both unadjusted and kurtosis-adjusted CNE as the exposure variable.

Results

Data were collected on 203 industrial steel workers exposed to complex, non-G noise; however only 178 of these workers, 132 from the rolling mill and 46 from the manufacturing plant, met our inclusion criteria. A total of 163 industrial workers exposed to G noise at a textile mill and meeting study inclusion criteria were included from a previous study (Zhao et al., 2010). Table 1 shows the distribution of age, gender and smoking status for subjects from these three plants. Table 2 provides a breakdown of average noise exposure, duration of exposure, kurtosis, unadjusted CNE and kurtosis-adjusted CNE, corresponding to the number of subjects exposed by plant and exposure source (worksite). Our field investigations, as well as subjects' personal questionnaires, indicated that none of the subjects used hearing protectors during the work periods under consideration.

Workers exposed to the complex noise (plant A and B) were slightly older (38.1±7.5 versus 31.7±8.7) than workers exposed to the continuous noise (plant C). The gender of subjects from plant A and B are all male while the number of male and female of subjects from plant C is evenly divided. The duration of the occupational exposure between the two populations from non-G and G groups (13.0±8.0 versus 12.7±8.4) was no statistical significant.

The $L_{Aeq,8h}$ noise exposures for all subjects varied from a low of 80 dBA to as much as 110 dBA. Peak levels of the individual impacts in the non-G noise reached as much as 140 dB peak SPL. The L_{eq} levels in the G noise environments were generally higher than those in the complex noise environments. Spectra analyses revealed a similar spectral pattern for both G and non-G noise exposures in this study.

Re-evaluating the kurtosis correction

This study investigated the ability to explain noise induced HTL shifts using three independent noise-related metrics: noise intensity, kurtosis, and duration of exposure among 178 subjects exposed in non-G noise environments. Several approaches were used. First, regression analyses were used to investigate the relative impact of age vs. cumulative noise exposure when exposure was represented by unadjusted vs. kurtosis-adjusted CNE (Equations (2) and (3) above). Second, we compared dose-response curves for noise induced hearing loss associated with G and non-G noise using both unadjusted and kurtosis-adjusted CNE.

Regression analysis—Our regression analyses used the average HTL at 3, 4 and 6 kHz of the worse ear as the dependent variable, with age and cumulative noise exposure as the explanatory variables. We tested whether adding current smoking status (yes/no; Plant A: 51.5% of smokers; and Plant B: 60.9%) significantly increased model fit, but it did not. Mixed model linear regression was used to evaluate whether plant (two plants) or area within plant (7 locations) introduced significant correlations into the model. As neither plant nor area had any significance impact on the equations, simple multiple linear regression was used.

Table 3 shows the results of two regression models – one using unadjusted CNE as the exposure variable, and the other using the kurtosis-adjusted CNE – compared to the base model which includes only age. Age alone is a fairly strong predictor of hearing loss with an R^2=0.239. The model using unadjusted CNE has an R^2=0.350 (an increase of R^2=0.111 over the base model), while the kurtosis-adjusted model has an R^2=0.386 (an increase of R^2=0.147 over the base model). The difference in R^2 between the two models is modest but significant ($p<0.001$). However, this modest change in overall model fit hides an important change in the model attribution of hearing loss from age to cumulative noise exposure. The standardized coefficient for age drops from 0.28 in the unadjusted model to 0.21 in the kurtosis-adjusted model (a 25% reduction), while the standardized coefficient for cumulative noise exposure increases from 0.39 to 0.48 (a 23% increase).

While the performance of the model was improved by using the kurtosis-adjusted metric, the relatively low value of the coefficient of determination (R^2) simply demonstrates that there is still a great deal of individual variation around human responses to noise that we cannot explain in these models. The fairly large 95% confidence intervals demonstrate that 178 subjects were not sufficient to produce a reasonably accurate prediction model. Much more human data are needed to verify the effectiveness of this model. However, this study indicates that the kurtosis in conjunction with an energy metric can help identify the hazardous potential of non-G noises that are not identified using conventional energy based metrics alone.

Estimating the dose response of hearing impairment to G and non-G noise using both the unadjusted and kurtosis-adjusted CNE

The data from the 178 workers exposed to non-G complex noise and 163 workers exposed to G noise were used to test the pilot study results demonstrating that the kurtosis-adjusted CNE could provide a unified metric for evaluating dose-response in mixed noise environments. Table 4 presents the calculated prevalence of AHFNIHL (% Loss) among G and non-G noise exposed workers for 5-dB strata of unadjusted and kurtosis-adjusted CNE.

When hearing loss was evaluated by 5-dB strata of unadjusted CNE, a clear difference between the prevalence of AHFNIHL among the G and non-G noise exposed workers in the 95, 100 and 105 dB strata was observed (see Table 4). The prevalence in the non-G noise exposed workers was significantly higher than that of the workers exposed to G noise with differences of 60% versus 30.4% in the 100 dB strata (analysis of variance, F=5.6, df=1 and p=0.02). In the 95 and 105 dB strata, though the differences are not statistically significant, the prevalence in the non-G noise exposed workers is ∼20% higher than that of the workers exposed to G noise.

However, when the kurtosis-adjusted CNE were used, these differences were diminished, because the adjusted CNE is greater than the unadjusted CNE for non-G noise exposed workers, but remains the same for G noise exposed workers.

Predicting hearing loss—Following the method introduced by Zhao et al. (2010), we independently fit a logistic regression model for the non-G and the G noise exposed workers to the dose-response data shown in Table 4. The results using both the unadjusted and adjusted CNE are shown in Fig.2.

It can be readily seen that using the unadjusted CNE yielded typical dose-response relationships for both exposure groups with the non-G noise exposed workers being shifted to the left and with a steeper slope relative to G noise exposed workers. This result indicates that the unadjusted CNE cannot be equally applied to G and non-G noise exposures, because complex non-G noise exposure is more hazardous to hearing than an energy equivalent continuous G noise.

However, when the kurtosis-adjusted CNE is substituted into the logistic regression, the dose-response curves for the two exposure groups overlap, essentially yielding an equivalent noise-induced effect (high frequency NIHL) for the two study groups. This finding suggests that a single measure of cumulative noise exposure to be applied to hearing loss estimates for either complex and Gaussian noise, or mixed exposures.

Discussion

This study demonstrated that a kurtosis adjustment of the cumulative noise exposure first put forward by Zhao et al. (2010) did, in fact, improve the association between measured occupational noise exposure and hearing loss among workers exposed to complex non-G noise. While the regression analyses controlling for age showed that using the kurtosis-adjusted CNE resulted in modest but significant improvement in the model coefficient of determination (R^2) from R^2=0.350 to R^2=0.386 (demonstrating the well-recognized large variability in human responses to noise exposure), other changes in the model may have more important. The profound switch in the attribution of hearing loss from age to noise exposure, if accepted, would have important implications for control of industrial noise and for compensation of noise-induced hearing loss. The observed reduced impact of age on hearing loss seen in our data seems occur when regression analyses of occupational studies of NIHL are combined with improved characterization of noise exposure. This effect was also seen in a previous analysis conducted by one of the authors (Heyer et al., 2011).

The second goal of this study was to evaluate that the same kurtosis-adjusted CNE would provide a uniform metric that could be applied to both Gaussian and complex noise for predicting noise associated hearing impairment. This study indicated that the unadjusted CNE produced separate AHFNIHL dose-response curves for Gaussian and complex noise exposures, with the curve for complex noise shifted left (to lower CNE values) and rising faster (steeper slope) than for Gaussian noise. In other words, complex noise exposures produce higher AHFNIHL prevalence rate than do CNE and spectrally equivalent G noise exposures. On the other hand, when kurtosis-adjusted CNE was used, the two dose-response curves fell on top of each other (Figure 2). This demonstrates the ability of the kurtosis-adjusted CNE to provide a consistent estimate of the prevalence of hearing loss across varied noise environments using a single metric.

Note that the G group from Plant C was evenly split between males and females, while the non-G group was exclusively male (Plants A and B). The male workers (N=82) were separated from the G group to compare the prevalence of AHFNIHL in only male workers (N=178) in the non-G group. Table 5 shows the calculated prevalence of AHFNIHL (% Loss) among G and non-G noise exposed male workers for 5-dB strata of unadjusted and kurtosis-adjusted CNE. When hearing loss was evaluated by 5-dB strata of unadjusted CNE, a clear difference between the prevalence of AHFNIHL among the G and non-G noise exposed male workers in all strata could still be observed (see Table 5). The prevalence in the male workers in the non-G group was significantly higher than that of male workers in the G group with differences of 66.7% versus 44.1% in the 105 dB strata (F=5.3, df=1 and p=0.02). In the 100 dB strata, though the differences are not statistically significant, the prevalence in the non-G noise exposed workers is ~16% higher than that of the workers exposed to G noise. When the kurtosis-adjusted CNE were used, these differences between the two groups were diminished as shown in Fig. 3. It is clear in Fig. 3 that using only male workers, the kurtosis-adjusted CNE could provide a consistent estimate of the prevalence of hearing loss across G and non-G noises. However, comparing Fig. 2 to Fig. 3 it can be seen that the performance of kurtosis-adjusted CNE using both female and male workers (N=163) in the G group in Fig. 2B is better than the one of using only male workers (N=82) in the G group in Fig. 3. Halving the number of subject in the G group clearly reduces the statistical power in this study.

The gender effect on NIHL has been studied by researchers and the results are not clear. Some studies demonstrated that women have better hearing at frequencies above 2000Hz than do men, with a difference of up to 20dB at 4000Hz. (Corso, 1963; Jerger et al., 1993; Gates et al., 1990; Pearson et al., 1995). Amos and Simpson (1995) reported a modest gender effect in that there was a greater female audiometric variability. But they indicated that this result may have been confounded by occupational noise exposure differences across gender categories. Hunter and Willot (1987) reported that there were no significant gender differences in high-frequency hearing have been noted in animal studies. Rosen et al. (1962) and Goycoolea et al. (1986) demonstrated that in societies free of hazardous noise exposure, the hearing thresholds of elderly women and men were equivalent. Krishnamurti's research (2009) showed that there was no significant gender difference in terms of noise-induced permanent threshold shift (NIPTS). Murphy and Gates (1999) argued that the poorer hearing at higher frequencies observed in men have generally been attributed to greater levels of exposure to occupational and recreational noise.

The information about average age, duration of exposure, CNE, NIPTS and the prevalence of AHFNIHL for both male and female workers from the G group in this study is listed in Table 6. Table 6(a) shows that the prevalence in percentage of AHFNIHL for male workers is generally higher than for female workers except at the 105 dB strata. However, the differences were not statistically significant. Table 6(b) presents the mean NIPTS values across audiometric frequencies for male and female workers from the G group. Both men and women showed equivalent NIPTS at frequencies below 2,000 Hz, while men had average 5 dB higher NIPTS at frequencies above 3,000 Hz. However, statistical analysis showed that there were no significant gender effects on NIPTS in this study. The slight higher NIPTS at high frequency for men in present study is more likely because men have more or greater accumulative noise exposures than women as showed in Table 6(c). It's an accepted fact that in general women have lower hearing thresholds than men, but there is no data to clearly suggest that women are actually less susceptible to noise than men. Thus, there is no reason to exclude female workers from the G group in this study. Further research including suitable number of females in non-G population will be conducted in the future to check the generalizability of this model.

As discussed above that audiometric asymmetry was common in our worker populations. A justification was made for using the worse ear as the indicative of the actual NIHL related to the measured level of environmental noise exposure. However, it could be arguable of using the worse ear since the ISO 1999 standard was developed using the better/average ear. Does the choice of the better/worse ear affect the outcome of the kurtosis adjustment? The data was reanalyzed using the better ear and Annex A to check the effectiveness of the kurtosis adjustment. Table 7 presents the calculated prevalence of AHFNIHL (% Loss) among G and non-G noise exposed workers for 5-dB strata of unadjusted and kurtosis-adjusted CNE using the better ear and Annex A. The prevalence in the non-G noise exposed workers was significantly higher than that of the workers exposed to G noise with differences of 48.9% versus 17.4% in the 100 dB strata (F=6.9, df=1 and p=0.01), and 54.9% versus 25% in the105 dB strata (F=8.9, df=1 and p=0.004). The prevalence rate of AHFNIHL for both G and non-G groups were decreased by using the better ear comparing to using the worse ear (from 64.4% to 49.8% for G noise group and from 57.3% to 48.3% for non-G group). The decline of prevalence was expected because of audiometric asymmetry. The dose-response relationships for long-term complex non-G noise and G noise exposures using the better ear are shown in Fig.4. From Fig. 2 and Fig. 4 it is clear that, whether using the worse or the better ear, the kurtosis-adjusted CNE could provide a consistent estimate of the prevalence of hearing loss across G and non-G noises. However, as mentioned above, if protection of worker's hearing is the objective then the worse ear should be used to establish the onset of NIHL

All the results in this study provide supporting evidence that the kurtosis-adjusted CNE metric may be a reasonable candidate for use in calculations to estimate the risk of NIHL from a wide range of noise exposure environments. Nevertheless, it would be necessary to replicate these findings using data acquired from a large number of workers with well-documented and diverse exposures to complex noise to provide the precision necessary for practical use in the evaluation of industrial NIHL.

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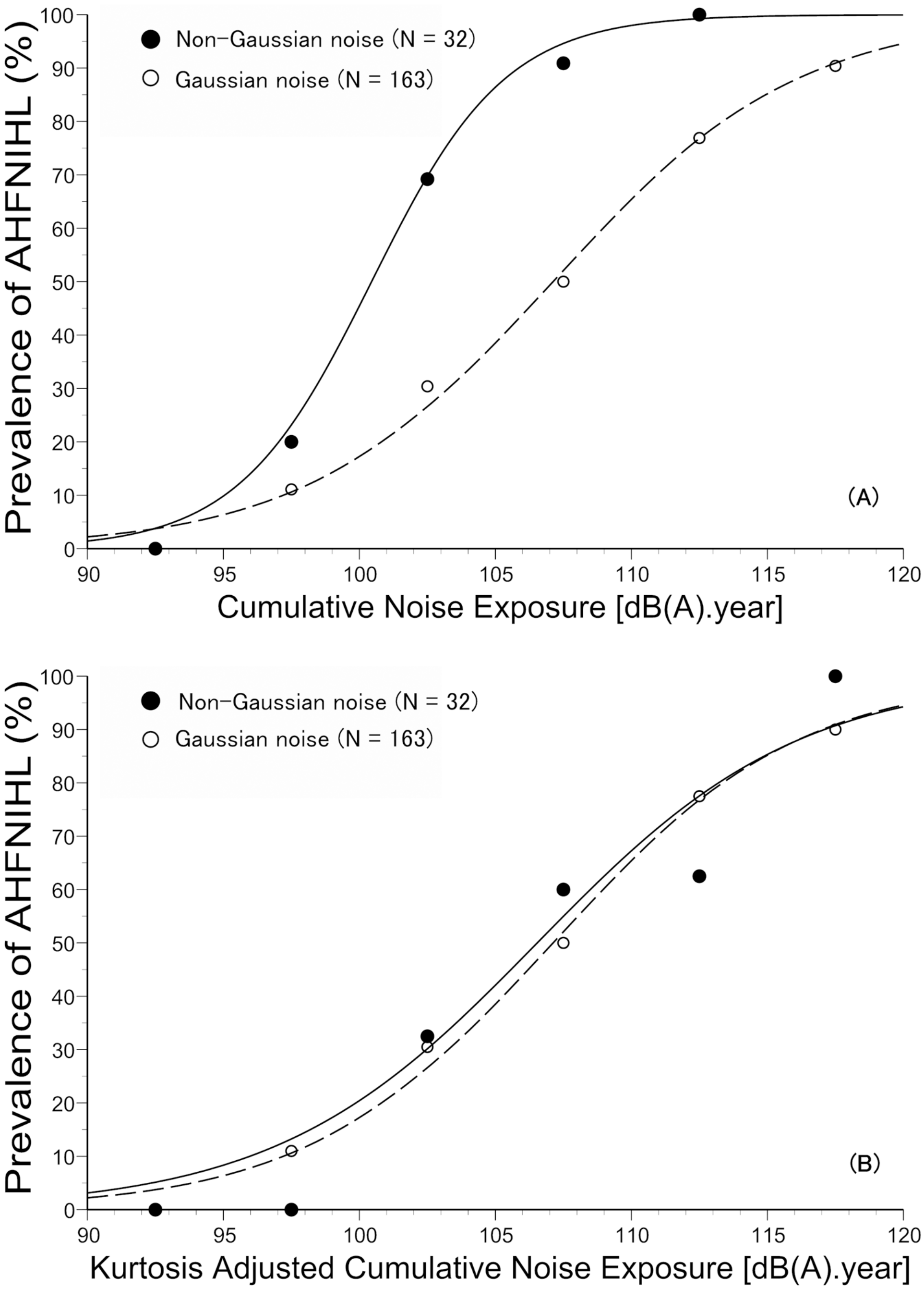

Figure 1.

The dose-response relationships for long-term non-G noise (N=32) and G noise exposure (N=163). (A) Original dose-response curves. (B) Kurtosis-adjusted dose-response curves.

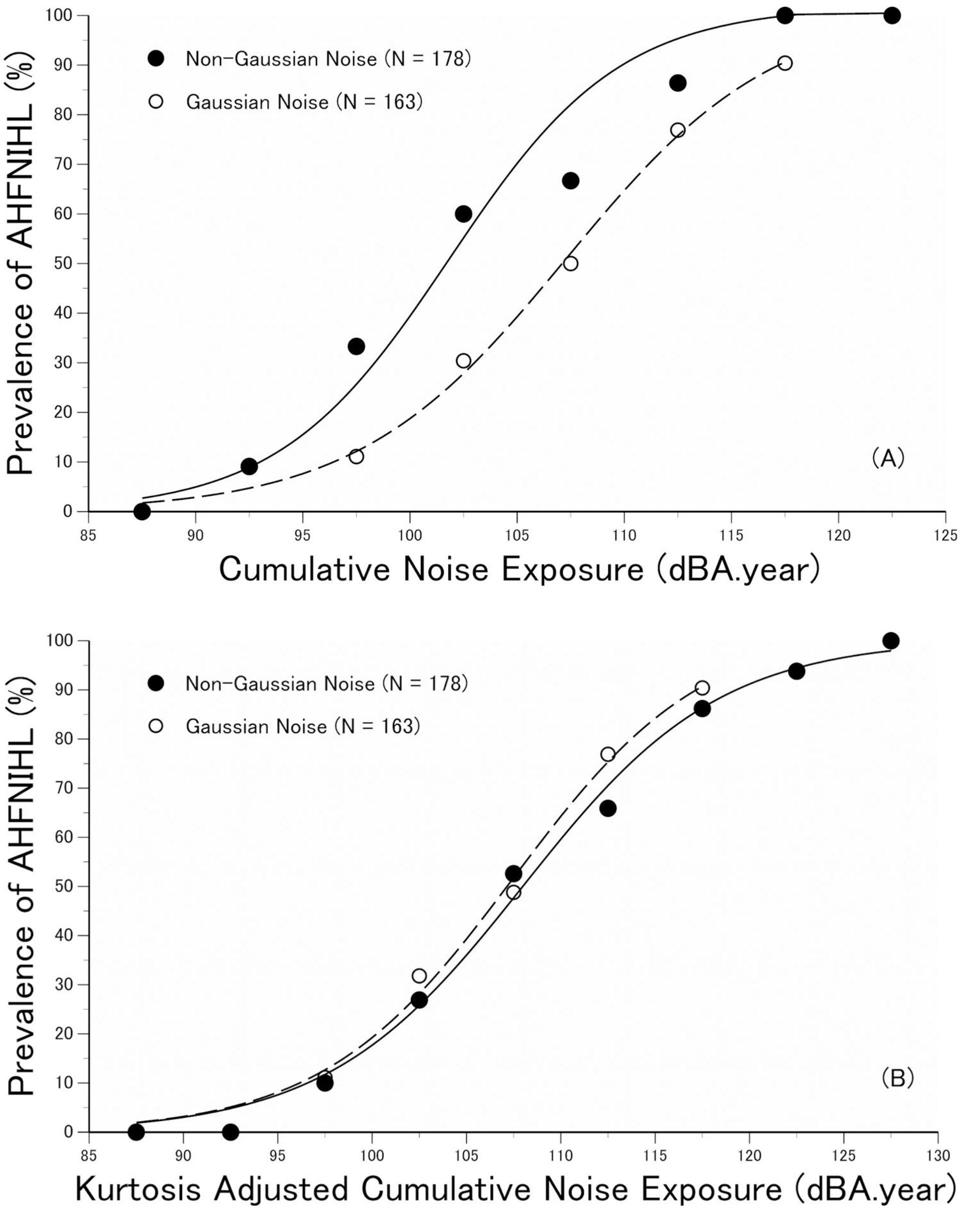

Figure 2.

The dose-response relationships for long-term non-G noise (N=178) and G noise exposures (N=163) using both (A) unadjusted CNE and (B) kurtosis-adjusted CNE.

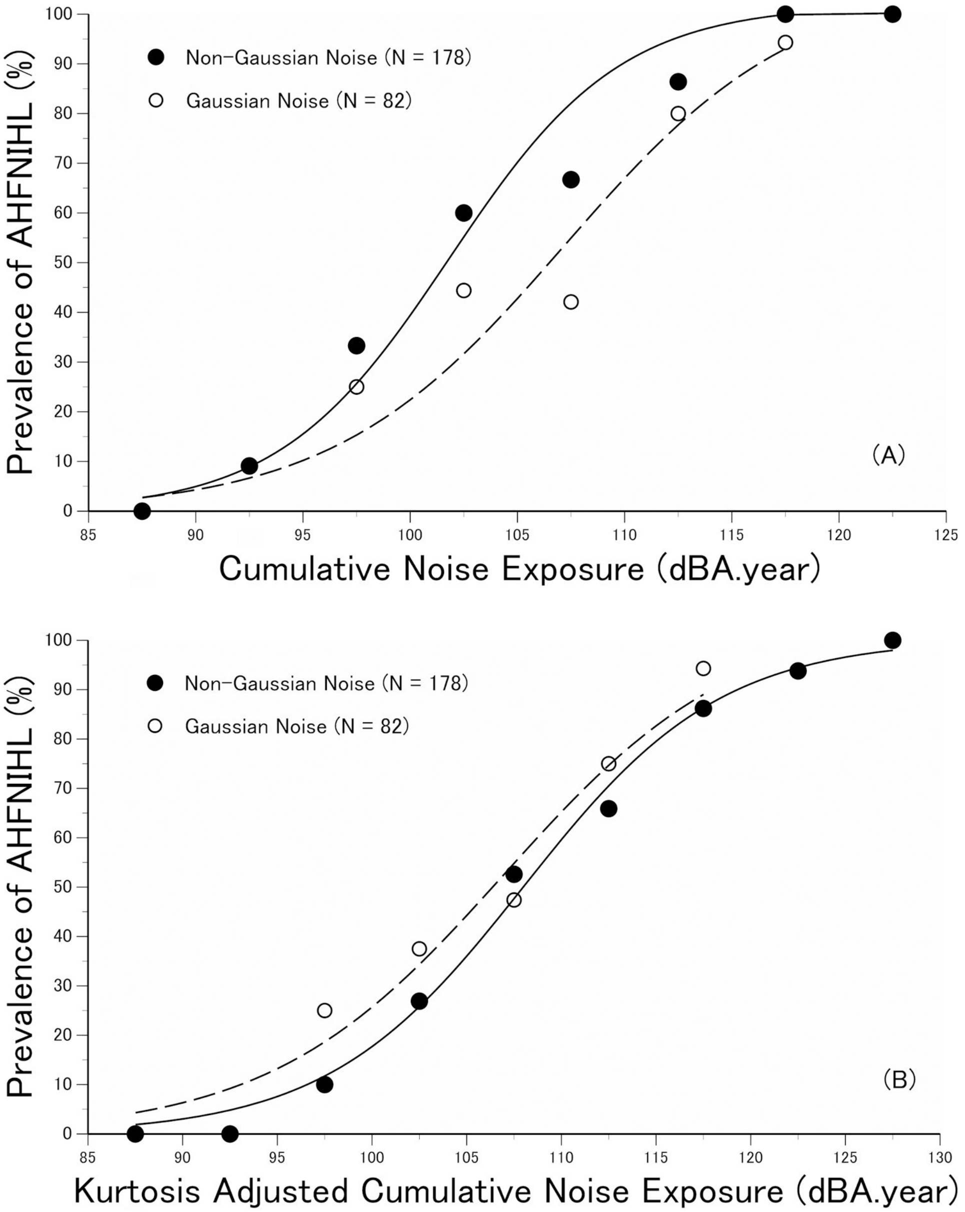

Figure 3.

The dose-response relationships among male workers exposed to non-G (N=178) and G noise exposures (N=82). (A) Original dose-response curves. (B) Kurtosis-adjusted dose-response curves.

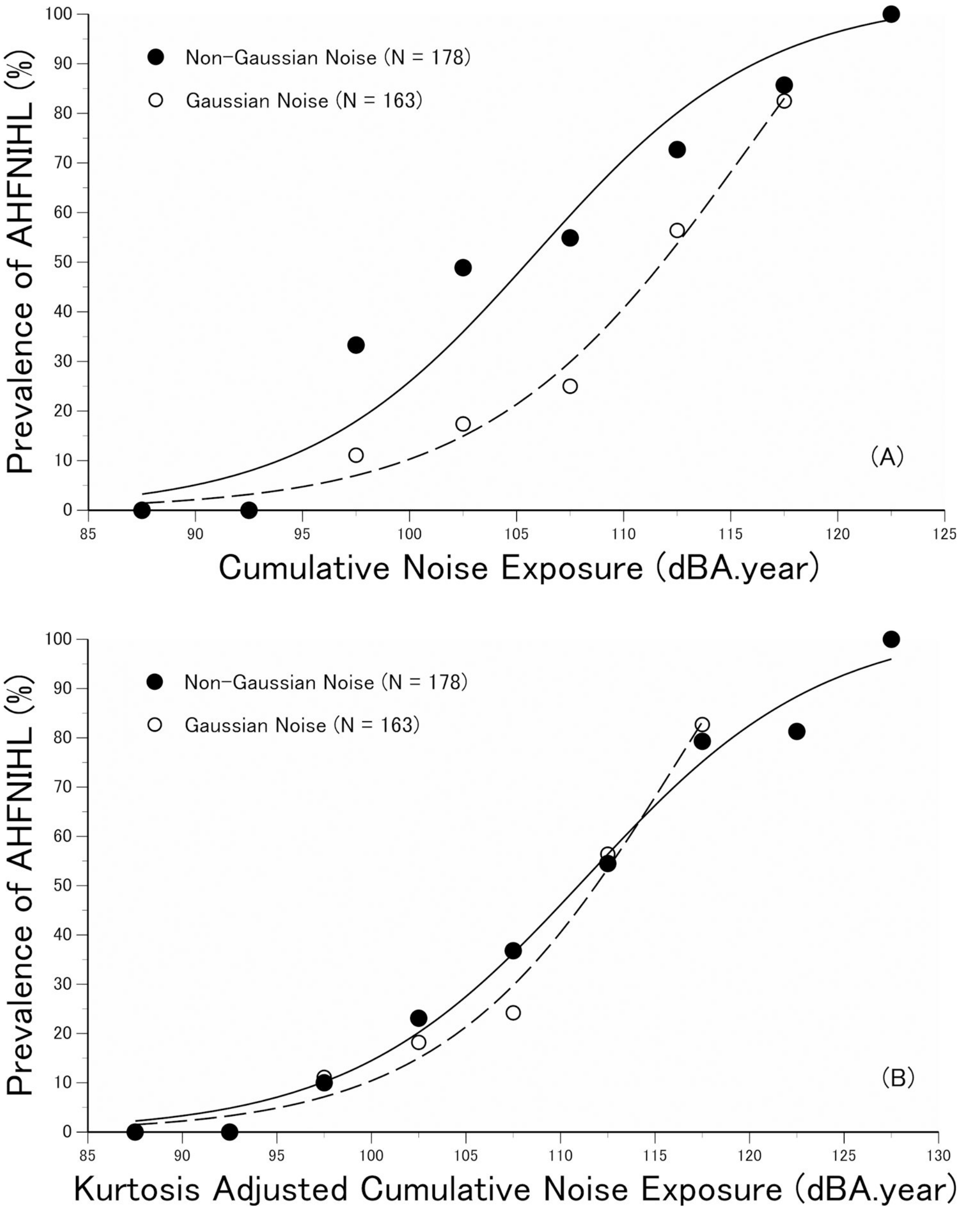

Figure 4.

The dose-response relationships for long-term non-G noise (N=178) and G noise exposures (N=163) using the better ear. (A) Original dose-response curves. (B) Kurtosis-adjusted dose-response curves.

Table 1

The distribution of age and gender for subjects from these three plants.

	Plant A	**Plant B**	**Plant C**
Male	132	46	81
Female	0	0	82
Smoking number	68	28	no data
Average age ± 1 s.d.	38.9 ± 7.7	35.8 ± 6.7	31.7 ± 8.7

Table 2

A breakdown of average noise exposure, duration of exposure, kurtosis, unadjusted CNE and kurtosis-adjusted CNE, corresponding to the number of subjects exposed by plant and exposure source (worksite).

Noise Type	Plant	Noise Source	N	Mean L_{Aeq}	Mean Yrs Exp	Mean β	Mean CNE	Mean Adj CNE
Complex	A	Tandem rolling	61	88.7 ± 5.0	13.7 ± 7.7	18.0 ± 8.6	99.2 ± 6.7	105.1 ± 8.4
	A	Hot rolling	32	93.1 ± 2.7	16.0 ± 8.5	10.3 ± 6.0	103.8 ± 6.2	108.1 ± 8.1
	A	Rolling finishing	14	97.4 ±2.9	21.1 ± 4.9	15.6 ± 3.9	110.6 ± 3.5	117.6 ± 4.0
	A	Steel rolling	25	99.8 ± 4.1	16.9 ± 5.0	16.5 ±11.8	111.8 ± 5.1	117.7 ± 6.4
	B	Light steel	22	94.9 ± 3.0	6.5 ± 4.4	99.6 ±80.3	102.3 ± 3.3	109.5 ± 6.4
	B	Heavy steel	17	97.6 ± 3.4	5.7 ± 2.7	86.1 ±64.5	104.7 ± 4.2	111.9 ± 5.4
	B	Assembly	7	94.9 ± 3.3	2.4 ± 1.5	127.9 ±63.9	98.0 ± 2.2	101.6 ± 3.6
Gaussian	C	Loom ZA205i	24	98.1 ± 2.1	9.0 ± 6.6	3.3 ± 0.4	106.1 ± 4.7	106.3 ± 4.8
	C	Loom 1511	75	105.4 ± 2.2	12.7 ± 8.6	3.1 ± 0.1	114.5 ± 4.7	114.8 ± 4.8
	C	Spinner FA507A	23	99.5 ± 2.2	14.2 ± 6.3	3.4 ± 0.3	110.3 ± 3.1	110.6 ± 3.2
	C	Spinner 1301	41	96.1 ± 2.7	13.3 ± 8.4	3.4 ± 0.4	105.0 ± 4.3	105.3 ± 4.4

N = number of subjects at each workstation; Plants: A = steel rolling mill; B = steel framework manufacturing plant; C = textile mill; ± =plus/minus 1 standard deviation.

Table 3

Results of regression models using unadjusted and kurtosis-adjusted CNE to estimate $\overline{\mathrm{HTL}}_{346}$ shift among 178 non-G exposed workers

Model 0: $\overline{\mathrm{HTL}}_{346}=b_0+b_1\mathrm{Age}$					**r^2=0.239**	**F=55.27**
	Coefficients		t Stat	P-value	B Lower 95%	B Upper 95%
	B	Beta				
Intercept	-69.82		-5.33	<0.0001	-95.67	-43.97
Age	0.55	.28	3.95	0.0001	0.27	0.82
Model 1: $\overline{\mathrm{HTL}}_{346}=b_0+b_1\mathrm{Age}+b_2\mathrm{CNE}$					**r^2=0.350**	F=47.21
	Coefficients		t Stat	P-value	B Lower 95%	B Upper 95%
	B	Beta				
Intercept	-69.82		-5.33	<0.0001	-95.67	-43.97
Age	0.55	.28	3.95	0.0001	0.27	0.82
CNE	0.80	.39	5.48	<0.0001	0.51	1.08
Model 2: $\overline{\mathrm{HTL}}_{346}=b_0+b_1\mathrm{Age}+b_2\mathrm{Adjusted\ \ CNE}$					**r^2=0.386**	F=55.04
	Coefficients		t Stat	P-value	B Lower 95%	B Upper 95%
	B	Beta				
Intercept	-69.23		-6.18	<0.0001	-91.36	-47.11
Age	0.40	.21	2.84	0.005	0.12	0.68
Adjusted CNE	0.80	.48	6.48	<0.0001	0.56	1.04

Note: CNE and (Kurtosis) Adjusted CNE are defined by Equations (2) and (3) in the text. B: unstandardized coefficients; Beta: Standardized coefficients.

Table 4

The prevalence AHFNIHL (% Loss) among workers exposed to non-G and G noise by 5-dB strata of unadjusted and kurtosis-adjusted CNE. The prevalence was calculated by using the worse ear.

Unadjusted CNE*							**Kurtosis-Adjusted CNE***						
CNE*	**Complex noise**			**Gaussian noise**			**CNE***	**Complex noise**			**Gaussian noise**		
	N_1	**N_2**	**%Loss****	**N_1**	**N_2**	**%Loss****		**N_1**	**N_2**	**%Loss****	**N_1**	**N_2**	**%Loss****
85~	6	0	*0*	-	-	-	*85~*	3	0	*0*	-	-	-
90~	11	1	*9.1*	-	-	-	*90~*	7	0	*0*	-	-	-
95~	33	11	*33.3*	9	1	*11.1*	*95~*	10	1	*10.0*	9	1	*11.1*
100~	45	27	*60.0*	23	7	*30.4*	*100~*	26	7	*26.9*	22	7	*31.8*
105~	51	34	*66.7*	40	20	*50.0*	*105~*	38	20	*52.6*	41	20	*48.8*
110~	22	19	*86.4*	39	30	*76.9*	*110~*	44	29	*65.9*	39	30	*76.9*
115~	7	7	*100*	52	47	*90.4*	*115~*	29	25	*86.2*	52	47	*90.4*
120~	3	3	*100*	-	-	-	*120~*	16	15	*93.8*	-	-	-
125~	-	-	-	-	-	-	*125~*	5	5	*100.0*	-	-	-
Total	178	102	*57.3*	163	105	*64.4*	*Total*	178	102	*57.3*	163	105	*64.4*

* dB(A)•year; ** AHFNIHL %; N_1=total workers in strata; N_2=workers with hearing loss in strata.

Table 5

The prevalence AHFNIHL (% Loss) among male workers exposed to non-G and G noise by 5-dB strata of unadjusted and kurtosis-adjusted CNE. The prevalence was calculated by using the worse ear.

Unadjusted CNE[*]							**Kurtosis-Adjusted CNE**[*]						
CNE[*]	**Complex noise**			**Gaussian noise**			**CNE**[*]	**Complex noise**			**Gaussian noise**		
	N_1	**N_2**	**%Loss**[**]	**N_1**	**N_2**	**%Loss**[**]		**N_1**	**N_2**	**%Loss**[**]	**N_1**	**N_2**	**%Loss**[**]
85~	6	0	*0*	-	-	-	*85~*	3	0	*0*	-	-	-
90~	11	1	*9.1*	-	-	-	*90~*	7	0	*0*	-	-	-
95~	33	11	*33.3*	4	1	*25.0*	*95~*	10	1	*10.0*	4	1	*25.0*
100~	45	27	*60.0*	9	4	*44.4*	*100~*	26	7	*26.9*	8	3	*37.5*
105~	51	34	*66.7*	19	8	*42.1*	*105~*	38	20	*52.6*	19	9	*47.4*
110~	22	19	*86.4*	15	12	*80.0*	*110~*	44	29	*65.9*	16	12	*75.0*
115~	7	7	*100*	35	33	*94.3*	*115~*	29	25	*86.2*	35	33	*94.3*
120~	3	3	*100*	-	-	-	*120~*	16	15	*93.8*	-	-	-
125~	-	-	-	-	-	-	*125~*	5	5	*100.0*	-	-	-
Total	178	102	*57.3*	82	58	*70.7*	*Total*	178	102	*57.3*	82	58	*70.7*

* dB(A)•year; ** AHFNIHL %; N_1=total workers in strata; N_2=workers with hearing loss in strata.

Table 6(a)

The prevalence AHFNIHL (% Loss) among male and female workers exposed to G noise by 5-dB strata of unadjusted CNE. The prevalence was calculated by using the worse ear.

Unadjusted CNE*						
CNE*	**Female**			**Male**		
	N_1	**N_2**	**%Loss****	**N_1**	**N_2**	**%Loss****
95~	5	0	*0*	4	1	*25.0*
100~	14	3	*21.4*	9	4	*44.4*
105~	21	12	*57.1*	19	8	*42.1*
110~	24	18	*75.0*	15	12	*80.0*
115~	17	14	*82.4*	35	33	*94.3*
Total	81	47	*58.0*	82	58	*70.7*

*dB(A)•year; **AHFNIHL %; N_1=total workers in strata; N_2=workers with hearing loss in strata.

Table 6(b)

The mean NIPTS values across audiometric frequencies for male and female workers from the G group.

Gender	**500 Hz**	**1 kHz**	**2 kHz**	**3 kHz**	**4 kHz**	**6 kHz**	**8 kHz**
Male	14.8±5.7	14.0±5.8	14.5±9.6	24.8±16.8	29.1±17.1	28.3±16.4	18.2±16.7
Female	15.5±5.0	13.8±5.6	13.9±8.9	18.8±13.7	24.3±15.4	24.2±14.4	13.4±11.1

Table 6(c)

The information of average age, duration of exposure, and CNE for both male and female workers from G group.

Gender	Worker number	Mean Age (yr)	Mean Yrs Exp.	Mean CNE
Male	82	33.4 ± 8.5	14.7 ± 8.7	111.5 ± 6.1
Female	81	29.9 ± 8.6	10.6 ± 7.6	109.7 ± 5.8

Table 7

The prevalence AHFNIHL (% Loss) among workers exposed to non-G and G noise by 5-dB strata of unadjusted and kurtosis-adjusted CNE. The prevalence was calculated by using the better ear.

Unadjusted CNE*							Kurtosis-Adjusted CNE*						
CNE*	Complex noise			Gaussian noise			CNE*	Complex noise			Gaussian noise		
	N_1	N_2	%Loss**	N_1	N_2	%Loss**		N_1	N_2	%Loss**	N_1	N_2	%Loss**
85~	6	0	*0*	-	-	-	*85~*	3	0	*0*	-	-	-
90~	11	0	*0*	-	-	-	*90~*	7	0	*0*	-	-	-
95~	33	11	*33.3*	9	1	*11.1*	*95~*	10	1	*10.0*	9	1	*11.1*
100~	45	22	*48.9*	23	4	*17.4*	*100~*	26	6	*23.1*	22	4	*18.2*
105~	51	28	*54.9*	40	10	*25.0*	*105~*	38	14	*36.8*	41	10	*24.4*
110~	22	16	*72.7*	39	22	*56.4*	*110~*	44	24	*54.5*	39	22	*56.4*
115~	7	6	*85.7*	52	43	*82.7*	*115~*	29	23	*79.3*	52	43	*82.7*
120~	3	3	*100*	-	-	-	*120~*	16	13	*81.3*	-	-	-
125~	-	-	-	-	-	-	*125~*	5	5	*100.0*	-	-	-
Total	178	86	*48.3*	163	80	*49.8*	*Total*	178	86	*48.3*	163	80	*49.8*

* dB(A)•year; ** AHFNIHL %; N_1=total workers in strata; N_2=workers with hearing loss in strata.