Role of the Kurtosis Statistic in Evaluating Complex Noise Exposures for the Protection of Hearing

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Objective: To highlight a selection of data that illustrate the need for better descriptors of complex industrial noise environments for use in the protection of hearing.

Design: The data were derived using a chinchilla model. All noise exposures had the same total energy and the same spectrum; that is, they were equal energy exposures presented at an overall 100 dB(A) SPL that differed only in the scheduling of the exposure and the value of the kurtosis, $\beta(t)$, a statistical metric. Hearing thresholds were determined before and after noise exposure using the auditory-evoked potential measured from the inferior colliculus in the brain stem. Cochlear damage was estimated from sensory-cell counts (cochleograms).

Results: (1) For equivalent energy and spectra, exposure to a high-kurtosis, non-Gaussian noise produced substantially greater hearing and sensory-cell loss in the chinchilla model than a low-kurtosis, Gaussian noise. (2) $\beta(t)$ computed on the amplitude distribution of the noise could clearly differentiate between the effects of Gaussian and non-Gaussian noise environments. (3) $\beta(t)$ can order the extent of the trauma as determined by hearing thresholds and sensory-cell loss.

Conclusions: The noise level in combination with the statistical properties of the noise quantified by $\beta(t)$ clearly differentiate the effects between both continuous and interrupted and intermittent Gaussian and non-Gaussian noise environments. For the same energy and spectrum, the non-Gaussian environments are clearly the more hazardous. The use of both an energy and kurtosis metric can better predict the hazard of a high-level complex noise than the use of an energy metric alone (as is the current practice). These results point out the need for a new approach to the analysis and quantification of industrial noise for the purpose of hearing conservation practice.

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INTRODUCTION

The role of the audiologist in hearing conservation practice is aimed at protecting workers from potentially hazardous noise environments through the analysis and control of noise exposure, the use of personal hearing protection, and hearing assessment procedures. Despite these efforts, noise-induced hearing loss (NIHL) remains among the 10 leading occupational diseases, affecting between 7 and 10 million people who work in noise above 85 dB(A) (Dobie 2001). Several factors contribute to our inability to protect more individuals from hazardous noise effectively. These include, for example, variability in an individual's susceptibility to noise, controversy on the trade-off rules for intensity and duration of exposure, and potentiation of NIHL by industrial and environmental toxins. Another important factor that may contribute to the high incidence of NIHL is that damage-risk criteria for noise exposure (Occupational Safety and Health Association 1981; International Standards Organization 1990; American National Standard Institute 1996; National Institute for Occupational Safety and Health 1998) rely only on an energy metric to quantify the exposure. Ample evidence exists that an energy-based protection strategy is not adequate. Exposures with the same total A-weighted energy can produce different degrees of hearing loss (Dunn et al. 1991; Lei et al. 1994; Lataye & Campo 1996; Hamernik & Qiu 2001; Harding & Bohne 2004; Qiu et al. 2006; Hamernik et al. 2007). Reports from the National Institute for Occupational Safety and Health (2002, 2005) indicated that there is a need for a more reliable predictor of NIHL. The main conclusion from these reports was that the generally accepted noise damage-risk criteria (ISO-1999) are "based on experimental data of mixed quality" that contribute to significant "limitations which constrain the ability to establish a widely accepted damage-risk criterion for impulsive and other sounds."

An energy metric alone should not be used to predict NIHL because it is insensitive to the effects of the temporal characteristics of a noise exposure known to be important in affecting hearing (Clark et al. 1987; Canlon et al. 1988; Hamernik & Ahroon 1998). Because temporal variables do not affect the energy metric and because there is an infinite number of different noise exposures characterized by the same equivalent noise level (L_{eq}), it seems reasonable that a metric that would incorporate both temporal and level variables might be a useful adjunct to the L_{eq} metric for predicting the risk of NIHL. One such metric is the kurtosis statistic. Kurtosis, of $\beta(t)$, is defined as the ratio of the fourth-order central moment to the squared second-order moment of the amplitude distribution. A distribution that is symmetric can still deviate from normality. Kurtosis is a metric that can be used to quantify the departure from the normality. For a normal distribution, $\beta(t) = 3$, whereas for distributions that are outlier prone have values of $\beta(t) > 3$ (leptokurtic). Examples of the former are Gaussian noises or unvoiced fricatives (/s/, /f/, and /sh/), whereas examples of the latter are running speech, impulse/impact noise, and complex noises. Complex noises are common in industrial environments where they consist of combinations of impact or noise-burst transients and continuous Gaussian noise; that is, they are non-Gaussian. All of the variables that characterize a non-Gaussian noise (e.g., transient peaks, inter-transient intervals, transient durations, crest factor) have an effect on the kurtosis value.

The development of metrics to predict occupational NIHL may be accomplished, in part, by determining how best to quantify the different types of noises found in an industry. Our own recent animal studies, for instance, have demonstrated that noises that have the same total energy and the same spectra but that differ considerably in their temporal structure can produce a different pattern and severity of hearing loss (Lei et al. 1994, Hamernik & Qiu 2001; Hamernik et al. 2003, 2007). More specifically, these studies have shown that (1) a time-averaged

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energy metric such as that currently used in noise damage-risk criteria is not adequate. (2) The statistical metric kurtosis, which quantifies the "peakedness" of an amplitude distribution, can differentiate between the hazardous effects produced by Gaussian and non-Gaussian noise environments. (3) $\beta(t)$ in combination with an L_{eq} metric is a better predictor of the risk for developing NIHL than the use of L_{eq} alone.

The objective of this study was to summarize some of our recent animal (chinchilla)-based noise exposure studies that illustrate how the kurtosis statistic can distinguish among the variety of noises that have the same energy but different temporal structures and subsequent effects on hearing. These results contribute to the goal identified in the National Institute for Occupational Safety and Health (2005) report that emphasized the need to develop an "international consensus on descriptors for impulsive sounds and procedures for applying results from tests on animals to models for the effect of impulsive sounds on hearing impairment of humans." The data summarized below illustrate one possible approach in achieving this goal.

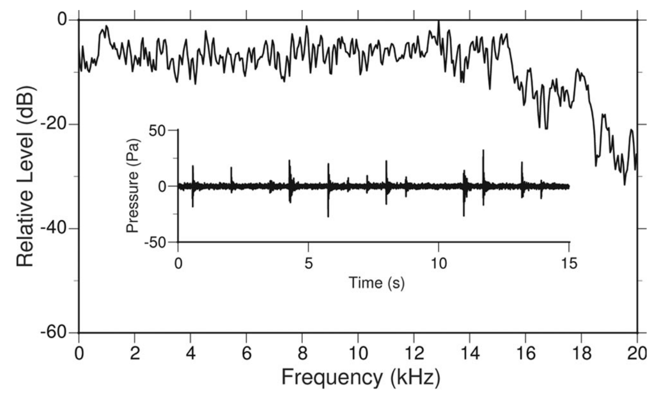

Fig. 1. The relative spectral level of a 40-sec sample of the unweighted 100 dB(A) SPL noise. This long-term spectrum was common to all of the noise-exposure conditions. The inset shows a 15-sec sample of one of the non-Gaussian waveforms. The impact peaks (maximum 138 dB) and interimpact intervals were varied randomly. The probability of an impact occurring in a 750-msec window was set at 0.6.

MATERIALS AND METHODS

The research protocol, using the chinchilla as the experimental model, followed a straightforward approach. Each animal's pre-exposure hearing thresholds were estimated using the auditory-evoked potential (AEP) from the inferior colliculus of the brain stem. The animals were then introduced to a noise exposure paradigm, and the AEP thresholds were measured during exposure as well as during a period of 30 days after which time the animals were killed and their sensory-cell population was quantified in the form of a cochleogram. Each noise-exposed group consisted of 7 to 16 animals.

Auditory-Evoked Potential

Each animal was anesthetized (intramuscular injection of ketamine [35 mg/kg] and xyalazine [1 mg/kg]) and made monaural by the surgical destruction of the left cochlea. During this procedure, a bipolar electrode was implanted, under stereotaxic control, into the left inferior colliculus and the electrode plug cemented to the skull for the recording of the AEP (Henderson et al. 1973; Salvi et al. 1982). After a 2-wk postsurgical recovery, three AEP pre-exposure audiograms were obtained on different days on each animal at octave intervals between 0.5 and 16.0 kHz. If the mean of the three audiograms, at more than one test frequency, fell beyond 1 SD of our laboratory normative pre-exposure thresholds established on a population of 1572 chinchillas, in the direction of poorer thresholds, the animal was rejected. Thirty days after the last day of exposure, three more AEP audiograms were collected on different days, and the mean was used to define the postexposure threshold from which the permanent threshold shift (PTS) was obtained. The animals were awake during testing and restrained in a yoke-like apparatus to maintain the animal's head in a constant position within the calibrated sound field. AEPs were collected to 20-msec tone bursts (5-msec rise/fall time) presented at a rate of 10/sec. Each sampled waveform was analyzed for large-amplitude artifact, and, if present, the sample was rejected from the average and another sample was taken. Averaged AEPs were obtained from 250 presentations of the 20-msec tone bursts. Thresholds were measured using an intensity series with 5-dB steps. Threshold was defined to be one-half step size (2.5 dB) below the lowest intensity that showed a "response" consistent with the responses seen at higher intensities. Additional details of the experimental methods may be found from the study of Ahroon et al. (1993).

Noise Exposure and AEP Testing Protocols

Each exposure had in common approximately the same broadband (0.125 to 20 kHz) spectrum that was reasonably flat between 0.125 and 10.0 kHz as shown in Figure 1. The inset in Figure 1 shows a 15-sec segment of a non-Gaussian noise. The peak level of the impacts in the non-Gaussian noise was variable with a maximum of 138-dB peak sound pressure level (SPL). The root mean squared SPL was 100 dBA for all exposures. All non-Gaussian exposures (i.e., $\beta[t] > 3$) consisted of a Gaussian noise with imbedded high levels of impact noise whose peak levels, interimpact intervals, and impact durations were randomly varied. The probability of an impact transient occurring in a 750-msec window was set at 0.6 for all non-Gaussian exposures. During noise exposure, the animals were confined to individual cages ($10 \times 11 \times 16$ in) with free access to food and water.

The data presented here were derived from two different noise exposure protocols. The noise in each of these protocols had the same spectrum and total energy and was presented at an overall level of 100 dBA. For the data presented in Figure 2, the three groups of animals were exposed for 24 hr/day for 5 days (protocol I). For this 5-day continuous exposure, complete AEP audiograms were obtained once daily. Testing took approximately 1½ hr. The mean of the five audiograms defined the asymptotic threshold in each of the exposed animals (Mills 1973). Although each group was exposed to a noise that had the same energy and spectrum, each exposure was designed to have a different value of $\beta(t)$. For the three groups of animals whose data are presented in Figure 3, the exposure was interrupted, intermittent, and had a time-varying (IITV) SPL, that is, one in which the level varies but remains above effective quiet (protocol II). The sound level was varied during each half-day exposure in an approximately Gaussian manner from ~70 to 105 dB SPL to yield an overall level of 100 dBA. The noise was on for 8 hr/day for 15 days. Each daily IITV

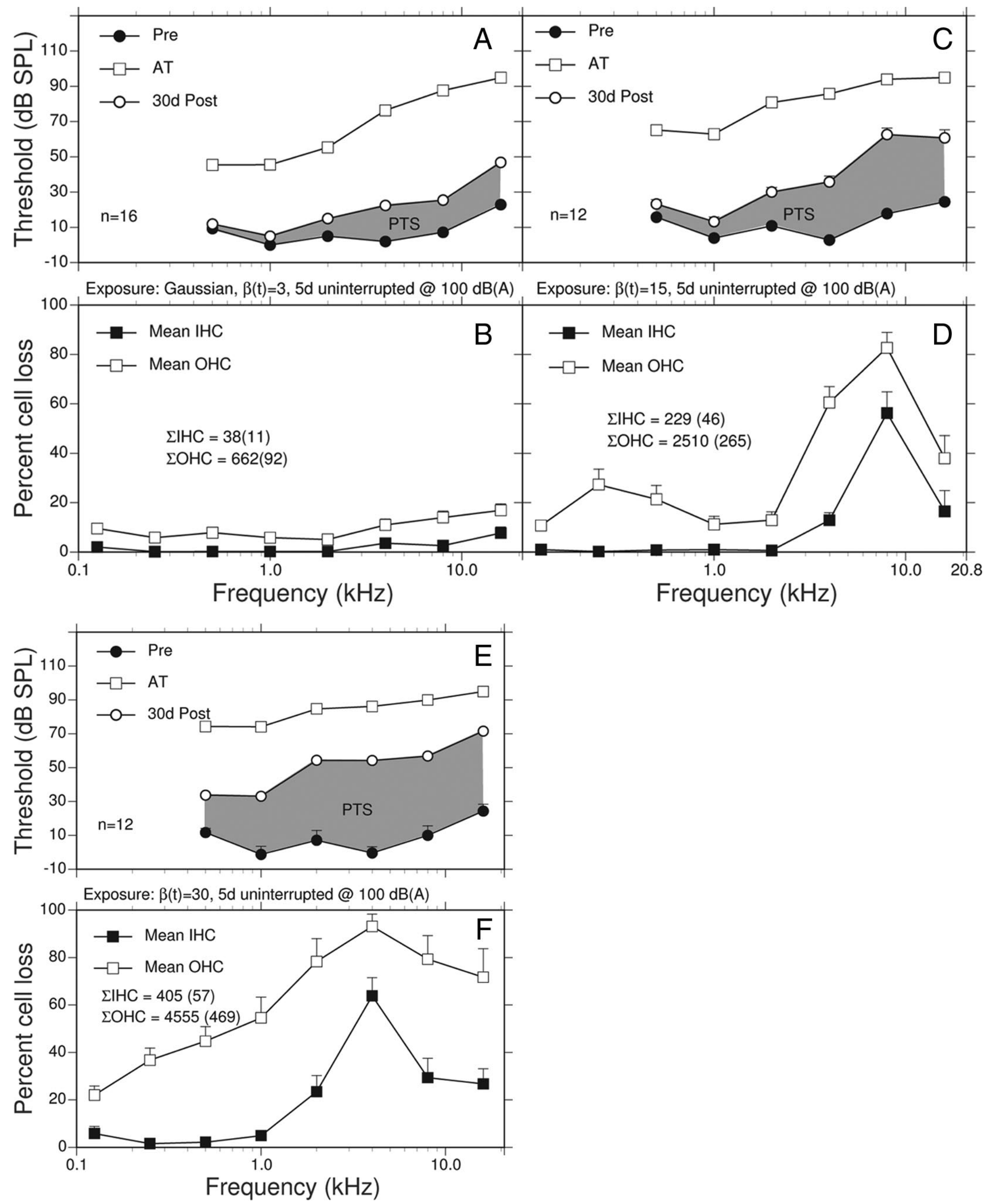

Fig. 2. Summary data for the protocol I, 5-day uninterrupted exposures. A and B, The Gaussian ($\beta[t] = 3$) reference group; (C and D) the non-Gaussian $\beta(t) = 15$ group; and (E and F) the non-Gaussian $\beta(t) = 30$ group. The upper panels show the group mean-evoked potential pre-exposure thresholds (Pre, ●), threshold at asymptote (AT, □), and the 30-day postexposure thresholds (○). The shaded region indicates the permanent threshold shift (PTS). The lower panels show the group mean percent inner hair cell (IHC, ■) and outer hair cell (OHC, □) loss averaged over octave band lengths of the basilar membrane centered at the test frequency. The group mean total number of IHC and OHC lost ([Sigma]IHC and [Sigma]OHC, respectively) are also given. The number in parentheses is the SE of the mean. Error bars indicate the SE. If no error bar is present, the SE is smaller than the size of the symbol.

exposure consisted of two 4.25-hr periods with an hour break in between. Each 4.25-hr exposure was interrupted for 15 min and each 5-day exposure sequence was separated by a 2-day break. The temporal features of these exposures were designed to simulate a realistic industrial work schedule and to have different values of $\beta(t)$.

The difference between thresholds measured after the first day and the mean of the thresholds measured after each of the last 3 days (T17–19) of the exposure was accepted as an estimate of threshold recovery or toughening (Tr; Clark et al. 1987). For the IITV exposures, animals were tested at the end of the daily exposure on days 1, 2, and 3 and on days 17, 18, and 19. In laboratory experiments using interrupted noise exposure paradigms that repeat over several days, the threshold shifts measured on successive days can decrease, that is, threshold improves despite the continuing daily exposure. This improvement of threshold has been referred to as a toughening effect. The difference between the initial thresholds and the

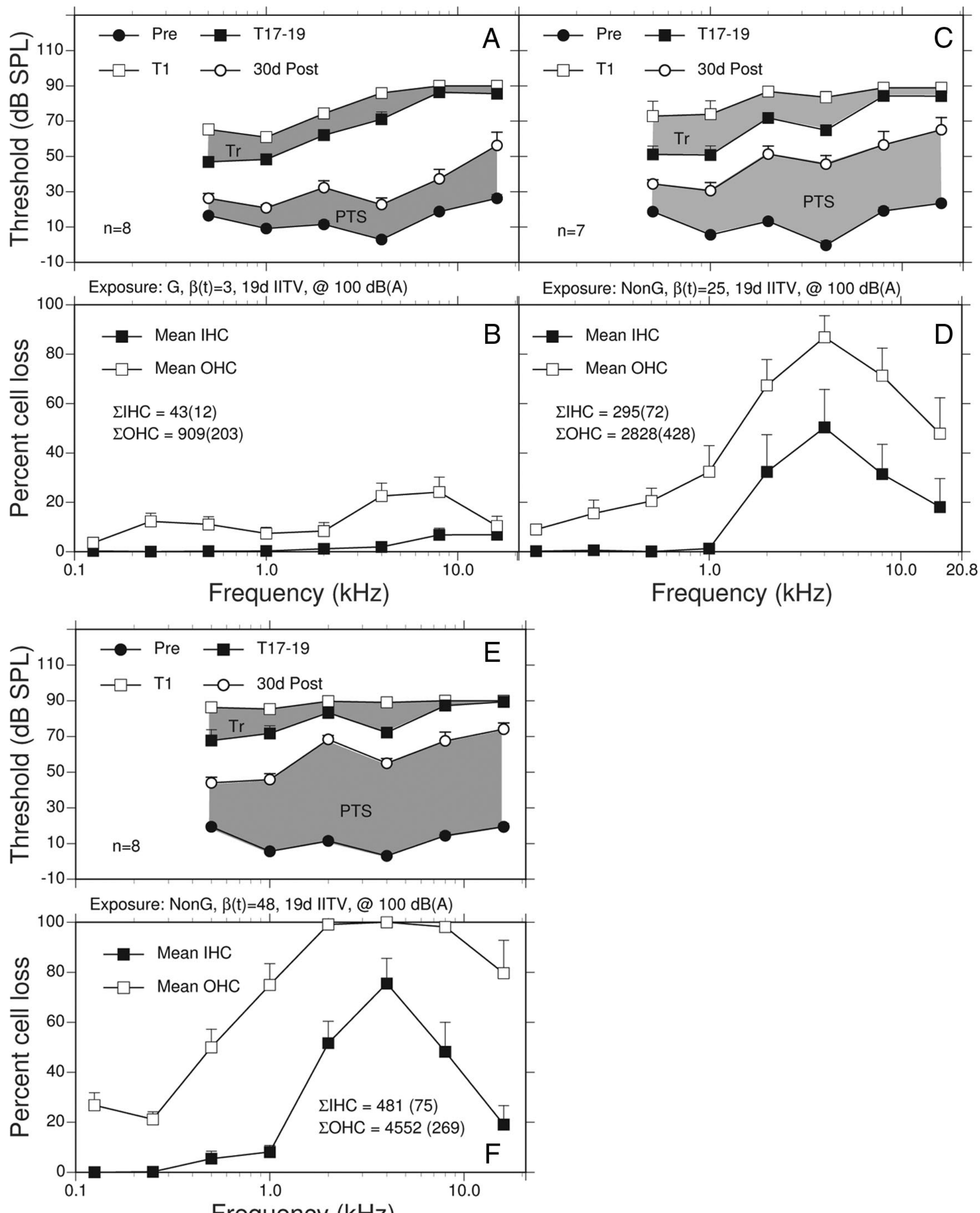

Fig. 3. Summary data for the protocol II, 19-day interrupted, intermittent, and time-varying (IITV) exposures. A and B, The Gaussian ($\beta[t] = 3$) reference group, (C and D) the non-Gaussian $\beta(t) = 25$ group, and (E and F) the non-Gaussian $\beta(t) = 48$ group. The upper panels show the group mean-evoked potential pre-exposure thresholds (Pre, ●), threshold after the first day of exposure (T1, □), the average of the thresholds measured after days 17 to 19 (T17–19, ■), and the 30-day postexposure thresholds (○). The shaded regions indicate toughening effect (Tr) and permanent threshold shift (PTS). The lower panels show the group mean percent inner hair cell (IHC, ■) and outer hair cell (OHC, □) loss averaged over octave band lengths of the basilar membrane. The group mean total number of IHC and OHC lost (ΣIHC and ΣOHC, respectively) is also given. The number in parentheses is the SE of the mean. Error bars indicate the SE. If no error bar is present, the SE is smaller than the size of the symbol.

thresholds at the end of the exposure will establish any "toughening" that might have occurred. For both exposure protocols, there was a reference group that consisted of a Gaussian exposure (i.e., $\beta[t] = 3$). The difference in threshold between the pre- and postexposure audiograms collected at least 30 days after noise exposure determined the amount of PTS for all exposure conditions. Details of the experimental methods can be found from the studies of Hamernik et al. (2003, 2007).

Noise Measurement and Analyses

The design and digital generation of the acoustic signal are detailed by Hsueh and Hamernik (1990, 1991). The noise was created using a loudspeaker (Electro-Voice Xi-1152/94) and power amplifiers (Model P1200 and P2000). The sound field was calibrated and recorded using a ½-in condenser microphone (Bruel and Kjaer, Model 4134), amplified by a measuring amplifier (Bruel and Kjaer, Model 2610), and digitalized by an analog-to-digital converter (National Instrument Inc., Model PCI-6221). The signal was sampled at 48 kHz in 16 bits with a recording duration of 5.5 min. Several segments of the signal were recorded at each cage and saved on a hard disk for an off-line analysis. The SPL and spectral data on both the impact and background noise were obtained from these recordings with programs developed using Matlab. The SPLs, across cages, in the middle of each cage varied $<\pm 1$ dB. During exposure, the sound level of the noise field was monitored with a Larson Davis 814 sound level meter using a ½-in microphone. For the non-Gaussian exposures, an average $\beta(t)$ was calculated by averaging the $\beta(t)$ from eight 5.5-min samples of the exposure waveform.

Histology

After the last AEP test protocol, each animal was killed under deep anesthesia, and the right auditory bulla was removed and opened to gain access to the cochlea for perfusion. Fixation solution consisting of 2.5% glutaraldehyde in veronal acetate buffer (final pH = 7.3) was perfused through the cochlea. After 12 to 24 hr of fixation, the cochlea was postfixed in 1% osmium tetroxide in veronal acetate buffer. Surface preparation mounts of the entire organ of Corti were prepared and missing inner hair cells (IHCs) and outer hair cells (OHCs) populations were countered. Missing cells were identified by the presence of a characteristic phalangeal scar. For purposes of this presentation, sensory-cell population data are presented as group averages (in percent missing) taken over octave band lengths of the cochlea centered on the primary AEP test frequencies and as the group mean total number of IHCs or OHCs missing. The mean sensory-cell population (i.e., OHC ~7272; IHC ~1873) used to establish the percent cell loss in octave band lengths of the cochlear is based on results obtained from 30 normal chinchillas (Hamernik et al. 1989). The data on sensory-cell loss were plotted as a function of frequency and location using the frequency-place map of Eldredge et al. (1981).

Statistical Analysis

Group mean threshold shifts and the group mean percent sensory-cell loss in octave band lengths of the cochlea were compared among the groups of animals for each noise exposure protocol using a two-way, mixed-model analysis of variance with repeated measures on one factor (frequency) using the SPSS Release 4.0 (or equivalent) statistical package. The probability of a type I error was set at 0.05. Statistically significant main effects of frequency were expected and found in all of the following analyses because of the frequency-specific nature of the audibility curve of the chinchilla and the noise-exposure stimulus. For this reason, main effects of frequency are not addressed in the following presentation of the results.

RESULTS

Protocol I Noise Exposures

Figure 2 shows the results from three of the protocol I exposure conditions. The upper panel of the figure shows the group mean pre-exposure thresholds, the amount of threshold shift incurred during exposure (asymptotic thresholds), and the 30-day postexposure thresholds at each AEP test frequency. The PTS, that is, the difference between the mean 30-day post- and pre-exposure thresholds, is shaded. The lower panels show the group mean percent IHC and OHC loss estimated over octave band lengths of the basilar membrane. Bars on all data points represent 1 SE of the mean. If a bar is not present, then the SE was smaller than the size of the datum symbol. A comparison of panels (a), (c), and (e) shows a clear and statistically significant (analysis of variance, $p < 0.05$) increase in the asymptotic thresholds and PTS as $\beta(t)$ increases from 3, the Gaussian condition, to 30. The high-kurtosis exposures produced the largest loss in sensitivity despite the exposure having the same spectrum and energy. A similar effect is seen in a comparison of panels (b), (d), and (f) where an increase in $\beta(t)$ also resulted in a statistically significant (analysis of variance, $p < 0.05$) increase in OHC and IHC loss. These three exposure conditions illustrate that noise exposures having the same energy and spectrum can have different effects on the auditory system and that the statistical metric, $\beta(t)$, can be used to identify the more hazardous exposures as well as order the degree of trauma. Additional details for this and other similar exposures can be found from the studies of Hamernik et al. (2003, 2007) and Qiu et al. (2006).

Protocol II Noise Exposures

The data shown in Figure 3 were derived from three protocol II exposures. These exposures were interrupted and intermittent with an SPL that varied in a roughly Gaussian manner during the course of each half day of the exposure. Although the scheduling of these IITV exposures was different from the conditions used to obtain the data shown in Figure 2, the total exposure energy and spectrum were the same. The form of the data presentation is similar to that described for Figure 2 except that the group mean thresholds measured at the end of the first day of the exposure are shown (T1) along with the group mean thresholds averaged during the last 3 days of the exposure (T17–19). The difference between these two threshold estimates is an indication of the amount of toughening and is shaded.

Two points can be made from this figure by comparing panels (a), (c), and (e) and panels (b), (d), and (f). (1) As with the protocol I exposures, there is a systematic increase in PTS and sensory-cell loss with an increase in the value of $\beta(t)$. (2) All the three IITV exposures produced a Tr that could be as much as 20 dB at the low frequencies, decreasing to little or no Tr at the highest frequencies. Additional details for this and other similar exposures can be found from the study of Hamernik et al. (2007).

Summary of Data Supporting the Use of $\beta(t)$ in the Evaluation of Noise Environments

A number of other different protocol I and II exposure conditions that were run over the past several years in our laboratory support the use of a kurtosis metric in the evaluation of complex noise environments. The results of these equivalent

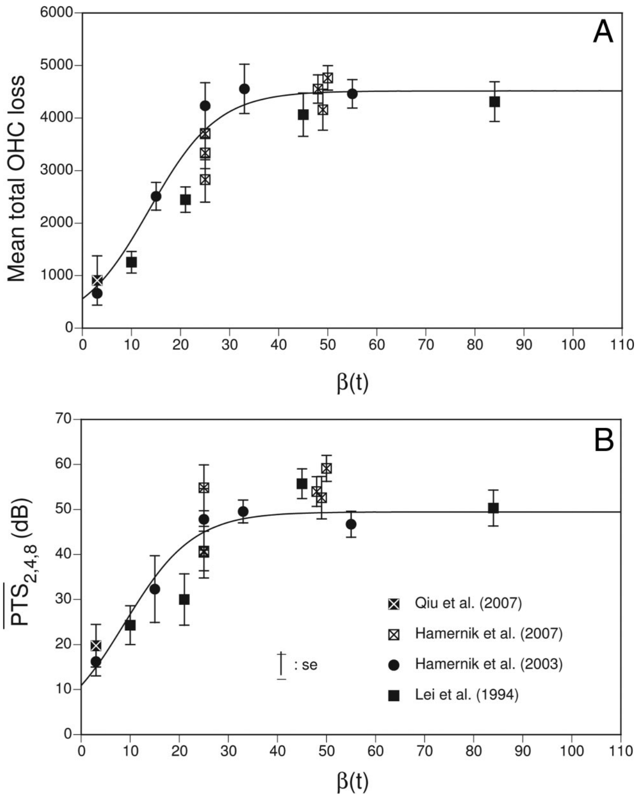

Fig. 4. A, The group mean total number of outer hair cells (OHC) missing as a function of $\beta(t)$. B, The group mean permanent threshold shift (PTS) averaged over the 2-, 4-, and 8-kHz auditory-evoked potential test frequencies ($PTS_{2,4,8}$) as $\beta(t)$ is increased. Data points were taken from the indicated references and represent groups of animals that have all been exposed to noise paradigms having the same energy (L_{eq} = 100 dB [A]) and spectrum. The noise exposures followed either a protocol I or II scheduling and differed only in the value of $\beta(t)$ or in the type of sound pressure level variation used in the protocol II exposures.

energy exposures and the references from which the data were extracted are summarized in Figure 4. The group mean PTS averaged over the 2-, 4-, and 8-kHz AEP test frequencies and the total OHC loss for these noise-exposed groups are plotted against $\beta(t)$. The data points were taken from the references identified in the previous two results sections and from Lei et al. (1994) and Hamernik and Qiu (2001). All exposures had the same total energy and spectrum. This figure reinforces the points that were made above. Specifically, for realistic exposure conditions, all exposures of the same energy do not produce the same amount of hearing and OHC loss. Rather, the temporal structure of the noise itself (i.e., the amplitude distribution quantified by the kurtosis metric) plays a significant role in determining the extent of auditory trauma. As $\beta(t)$ increases so does hearing and sensory-cell loss. For a given energy level, the degree of trauma reaches an asymptotic plateau for $\beta(t) > 50$. For the highest values of $\beta(t)$, there is as much as four times the OHC loss and up to ~30-dB additional PTS compared with the Gaussian, $\beta(t) = 3$ exposure.

DISCUSSION

After many years of research, we are still unable to predict the NIHL that will be sustained by an individual in a given noise environment, thus limiting our ability to establish acceptable damage-risk criteria. Current exposure standards are based on a tradeoff between noise intensity and exposure duration but are insensitive to the temporal distribution of sound energy. The likelihood that the hearing loss will increase with an increase in SPL or an increase in exposure duration is not debatable. This review has provided evidence that the use of an energy metric in combination with the kurtosis statistic can be used to refine our ability to estimate the hazards to hearing from the diversity of complex noise environments found in the industry. The kurtosis metric can separate exposed subjects into similarly exposed groups in a quantitative way. These data have shown that (1) an understanding of the temporal structure of a noise exposure is critical to predicting its hazard; (2) an energy metric in combination with the kurtosis metric can differentiate between the effects of Gaussian and non-Gaussian noise environments on the auditory system; and (3) $\beta(t)$ can order the extent of auditory trauma from high-level complex noise exposures.

A frequency-weighted energy metric in combination with the statistical metric, kurtosis, may provide necessary and possibly sufficient information to evaluate the potential of any industrial noise environment to cause hearing loss. The data demonstrate that $\beta(t)$ can refine our ability to predict the hazard to hearing associated with the temporal distribution of energy and provide a foundation for a more generalized and more accurate approach to the analysis and quantification of industrial noise for the purpose of hearing conservation practice.

Virtually all noise-induced effects found in animals have had their correlates in the human condition (Erlandsson et al. 1987). However, except for the use of an L_{eq} metric and weighting functions, there is still no generally accepted strategy for relating the various parameters that can be extracted from a noise analysis to their ultimate effect on hearing and sensory-cell loss in humans. Animal model studies such as those described above provide a starting point for developing a different approach to the evaluation of hazardous noise environments. However, studies involving large numbers of workers with well-documented exposures will be required before a relation between a metric such as the kurtosis and the risk of hearing loss can be refined.

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In conducting this research the investigators adhered to the "Guide for the Care and Use of Laboratory Animals," prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council (DHHS Publication No. [NIH] 86-23, revised 1985).

This research adhered to the ethical principles for conducting animal research. It received approval from the Institutional Animal Care and Use Committee of the State University of New York at Plattsburgh (protocol 77).

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Kurtosis corrected sound pressure level as a noise metric for risk assessment of occupational noises

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Current noise guidelines use an energy-based noise metric to predict the risk of hearing loss, and thus ignore the effect of temporal characteristics of the noise. The practice is widely considered to underestimate the risk of a complex noise environment, where impulsive noises are embedded in a steady-state noise. A basic form for noise metrics is designed by combining the equivalent sound pressure level (SPL) and a temporal correction term defined as a function of kurtosis of the noise. Several noise metrics are developed by varying this basic form and evaluated utilizing existing chinchilla noise exposure data. It is shown that the kurtosis correction term significantly improves the correlation of the noise metric with the measured hearing losses in chinchillas. The average SPL of the frequency components of the noise that define the hearing loss with a kurtosis correction term is identified as the best noise metric among tested. One of the investigated metrics, the kurtosis-corrected A-weighted SPL, is applied to a human exposure study data as a preview of applying the metrics to human guidelines. The possibility of applying the noise metrics to human guidelines is discussed. © *2011 Acoustical Society of America*. [DOI: 10.1121/1.3533691]

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I. INTRODUCTION

Most noise guidelines currently in use such as International Standard Organization (ISO-1999, 1990) recommend safe levels of noise exposure based on the equal energy hypothesis (EEH). The EEH assumes that hearing loss is a function of only the total exposure energy, independent of the temporal characteristics of the noise (Robinson, 1968; Prince *et al*., 1997). The EEH based approach has been used to establish and implement noise guidelines because of its simplicity. However, the approach is generally considered appropriate for steady-state noise but not for complex noise, a steady-state noise embedded with impulsive noises (Ahroon *et al*., 1993). Some researchers have argued for the application of EEH in complex noise environments (Atherley and Martin, 1971; Guberan *et al*., 1971; Atherley, 1973), which however has largely been rebutted both by laboratory studies (Dunn *et al*., 1991; Hamernik and Qiu, 2001; Lei *et al*., 1994; Hamernik *et al*., 1974) and by epidemiological studies (Sulkowski and Lipowczan, 1982; Thiery and Meyer-Bisch, 1988).

The current guideline of National Institute for Occupational Safety and Health (NIOSH, 1998) suggests a 140-dB sound pressure level (SPL) limit should be used for impulsive noise, and the 85-dBA permissible exposure limit (PEL) with a 3-dB exchange rule should be used for complex noises. It also notes that "(if) the effects are synergistic, the 85-dBA PEL and 3-dB exchange rule would still be protective to a smaller extent than for the steady-state noise." This suggests the need for more research to determine: (1) if synergistic effects exist in the complex noise problem and (2) a quantification of the synergistic effects has to be included in future noise guidelines. The first issue, existence of synergetic effects was quite clearly confirmed by many animal noise exposure studies (Dunn *et al*., 1991; Lei *et al*., 1994). The second issue, the need for quantification of synergetic effects has motivated this study.

Recent studies on animal exposure (Hamernik and Qiu, 2001; Hamernik *et al*., 2003b) have shown that kurtosis effectively discriminates the risk of hearing loss in chinchilla for noise exposures with the same level and different temporal characteristics. Thus, SPL combined with a kurtosis correction term may serve as a good noise metric for assessment of the risk of noise of widely different temporal characteristics. Zhao *et al*. (2010) combined an energy-based metric with a temporal correction term to evaluate human noise exposure study data. In this work, the kurtosis correction was made through the exposure time. The correction term was determined to match dose-response relationship (DRR) of the two groups, respectively, exposed to a complex noise environment and a Gaussian noise environment. Because the study used only one set of data, generality of the correction form has yet to be established. In this work, the best form of the kurtosis corrected SPL is *identified* based on chinchilla noise exposure test data, taking advantage of abundant DRR obtained from direct, controlled experiments. The result is applied to the human exposure data obtained by Zhao *et al*. (2010) as a preview of possible application of the result for human.

II. EXPERIMENTAL DATA

The current study uses noise exposure data for 273 chinchillas of 23 groups provided by collaborators at SUNY Plattsburgh. Each of the 23 animal groups consisting of 9–16 chinchillas was exposed to a specially designed, different noise environment. Eighteen groups were exposed to 100-dBA

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noises (1 Gaussian, 17 complex), two groups to 95-dBA noises (1 Gaussian and 1 complex), and three groups to 90-dBA noises (1 Gaussian and 2 complex). Animals were exposed to a given noise for 24-h per day, for five consecutive days. The hearing threshold level (HTL) was measured from the auditory evoked potential (AEP) at 0.5, 1, 2, 4, 8, and 16 kHz for each animal before the exposure, daily during the test and 30 days after the completion of the exposure. From the AEP data, permanent threshold shift (PTS) and temporary threshold shift (TTS) are calculated. Outer hair cell (OHC) losses and inner hair cell (IHC) losses in 0.5, 1, 2, 4, 8, and 16 kHz bands were also measured. The noise data digitally recorded for 5-min with the 48 kHz sampling was given as a part of the data to the authors. More detailed descriptions of the noises and experimental protocols are available in various publications (Hamernik *et al.*, 1989; Hamernik *et al.*, 2003a; Hamernik *et al.*, 2007). The PTS data is used as the primary measure in the current research because it is used as the basis for the noise induced hearing loss (NIHL) in all noise guidelines.

Availability of the digitally recorded noise time histories makes the exposure data highly valuable, as it enables reprocessing of the data from different angles. The analytic wavelet transform (AWT) developed by Zhu and Kim (2006) and Zhu *et al.* (2009) was applied in this work to obtain time histories of the full-octave frequency components at 0.5, 1, 2, 4, 8, and 16 kHz. From these time histories, equivalent SPL (L_{eq}) of the frequency components was calculated as listed in Table I. Fast Fourier transform (FFT) can also be applied instead of AWT to obtain the frequency components. Kurtosis of the noise was calculated from the original pressure time histories.

Kurtosis is defined as the fourth standardized moment about the mean of the data:

$$\frac{E(x-m)^4}{s^4}, \qquad (1)$$

where s is the standard deviation of x, $E(\cdot)$ represents the expected value of quantity, m is the mean of x. Kurtosis describes the peakedness of a distribution, which is independent of the overall level and was suggested as a metric of impulsiveness by Erdreich (1985). Kurtosis of Gaussian noises is approximately 3 as represented in noises G-61, G-47, and G-57 in Table I.

III. DEVELOPMENT OF THE NEW NOISE METRIC

The performance of the noise metric is evaluated by its correlation with the NIHL defined in a way most compatible with the definition used in human guidelines. Unacceptable occupational *hearing loss* is defined in NIOSH guideline (NIOSH, 1998) by material hearing impairment, which is having a 25-dB or higher HTL averaged for 1, 2, 3, and 4 kHz. As the PTS of chinchillas was measured at 0.5, 1, 2, 4, 8, and 16 KHz, missing the 3 kHz component, the average of

TABLE I. The overall and frequency-by-frequency equivalent SPLs (L_{eq}) and kurtosis of the 23 noises used to expose chinchillas. Frequency-by-frequency L_{eq} is calculated for a full-octave component at 0.5, 1, 2, 4, 8, and 16 kHz center frequencies. The kurtosis value is calculated from the pressure time history of the noise. $PTS_{5124} = \frac{1}{4}(PTS_5 + PTS_1 + PTS_2 + PTS_4)$, where PTS_5, PTS_1, PTS_2, PTS_4 are the average of the PTS of the chinchillas in the group measured at 0.5, 1, 2, 4, 8, and 16 kHz.

Group Index	L_{eq} (dB) Overall	0.5 kHz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz	β (kurtosis)	PTS_{5124} (dB)
G-44	101.1	80.7	92.9	93.00	95.4	93.3	93.9	32.7	29.39
G-49	101.5	84.5	93.8	93.6	95.4	93.17	92.7	33.2	39.56
G-50	101.6	85.5	85.4	96.9	90.99	95.15	94.6	20.8	10.41
G-51	100.3	80.0	95.7	94.3	94.49	90.29	85.4	101.8	22.13
G-52	102.5	86.7	97.5	94.8	94.56	93.98	93.7	52.9	28.17
G-53	101.1	82.8	95.2	94.0	96.06	92.7	89.4	97.9	27.39
G-54	102.0	85.2	96.1	94.1	94.0	93.08	94.6	35.9	23.97
G-55	103.3	94.7	93.1	89.5	91.2	95.9	94.1	25.6	30.93
G-59	103.4	99.2	93.4	93.7	88.6	92.8	93.4	30.9	13.64
G-60	102.4	86.1	96.1	94.1	95.0	94.2	94.7	35.6	29.17
G-61	102.7	91.4	89.5	87.8	92.1	96.5	97.09	3.0	9.5
G-63	100.9	83.5	98.4	94.2	92.0	85.6	79.2	117.1	34.20
G-64	102.4	86.9	93.2	91.3	93.3	95.5	97.0	8.4	20.00
G-65	102.1	94.2	93.2	89.3	90.0	94.3	88.2	118.8	24.05
G-66	102.8	90.6	90.9	89.9	92.8	98.3	95.5	14.8	17.23
G-68	103.1	94.2	93.6	89.6	90.2	95.4	95.5	58.4	22.05
G-69	99.9	69.3	74.3	99.3	91.1	82.2	75.2	77.4	9.1
G-70	101.5	85.2	92.3	92.6	95.6	93.2	93.6	27.1	25.21
G-47	92.4	80.7	79.3	78.2	82.05	86.4	86.6	3.0	1.3
G-48	92.6	75.9	87.2	85.08	84.4	83.4	84.3	33.3	6.16
G-56	93.4	82.3	81.4	80.4	83.1	89.2	84.9	36.04	4.5
G-57	97.3	86.8	85.6	83.3	85.5	90.8	91.5	3.0	8.0
G-58	96.4	79.5	91.2	88.6	88.4	87.3	87.9	41.5	13.23

PTS at 0.5, 1, 2, and 4 kHz or at 1, 2, and 4 kHz could be used as an approximate definition of NIHL in the correlation study. In this study, the former PTS_{5124} is chosen, which is defined as follows:

$$PTS_{5124} = \frac{1}{4}(PTS_5 + PTS_1 + PTS_2 + PTS_4), \quad (2)$$

where PTS_5, PTS_1, PTS_2, and PTS_4 are the average of PTS measured at 0.5, 1, 2, and 4 kHz from chinchillas in each group. PTS_{5124} of each of the 23 groups of chinchillas is shown in the last column of Table I.

A. Design of the noise metric

While kurtosis is a very good differentiator of the risk of noises of the same energy but different temporal characteristics, it cannot be used as a noise metric by itself because it is an energy-independent parameter. For example, Gaussian noises of 50- and 100-dBA, which clearly have different noise risks, have the same kurtosis value. Therefore, it is logical to incorporate kurtosis with the SPL to create the new noise metric. After testing several alternatives, the basic form of the new metric was determined as follows:

$$L'_{eq} = L_{eq} + \lambda \log_{10}\frac{\beta}{\beta_G}, \quad (3)$$

where L'_{eq} is the kurtosis corrected L_{eq}, λ is a positive constant to be determined from the dose-response correlation study, β is the kurtosis of the noise, and β_G is the kurtosis of the Gaussian noise. Notice that no correction is made for a Gaussian noise. A complex noise has a kurtosis higher than that of β_G; therefore, it has a positive correction term that represents the higher risk of the noise.

Six noise metrics shown in Table II are compared for their correlations with NIHL, which include two traditional metrics without a kurtosis correction term: equivalent and A-weighted equivalent SPLs, L_{eq}, and L_{Aeq}. The third metric without a correction term, $L_{eq,5124}$, is defined as

$$L_{eq,5124} = \frac{1}{4}(L_{eq,5} + L_{eq,1} + L_{eq,2} + L_{eq,4}), \quad (4)$$

where $L_{eq,5}$, $L_{eq,1}$, $L_{eq,2}$, $L_{eq,4}$ are equivalent SPLs of the 0.5, 1, 2, and 4 kHz full-octave components, respectively. $L_{eq,5124}$ is chosen by matching its form with the form of the NIHL defined in Eq. (4) expecting a good performance based on the cochlea position theory (Zwislocki and Nguyen, 1999; Price, 1979). L'_{eq}, L'_{Aeq} and $L'_{eq,5124}$ in Table II are kurtosis corrected versions of the first three metrics according to the scheme in Eq. (3). It is noted that $L_{eq,5124}$, L'_{eq}, L'_{Aeq} and $L'_{eq,5124}$ are new noise metrics studied for the first time in this paper.

TABLE II. Results of regression analysis of the noise metrics as functions of PTS_{5124}. λ is the coefficient of the kurtosis correction term and r^2 is the r-square value (square of the correlation coefficient) between the metric and NIHL defined as PTS_{5124}.

Metric number	Metric	λ	r^2 value
1	L_{eq}	N/A	0.41
2	L_{Aeq}	N/A	0.46
3	$L_{eq,5124}$	N/A	0.61
4	$L'_{eq} = L_{eq} + \lambda \log_{10}\frac{\beta}{\beta_G}$	4.80	0.54
5	$L'_{Aeq} = L_{Aeq} + \lambda \log_{10}\frac{\beta}{\beta_G}$	4.04	0.54
6	$L'_{eq,5124} = L_{eq,5124} + \lambda \log_{10}\frac{\beta}{\beta_G}$	3.07	0.67

B. Correlation study

The correlation analysis of the noise metric and the NIHL (PTS_{5124}) is conducted by applying a linear regression analysis to 23 pairs of the metric and PTS_{5124} data. For the first three metrics with no correction term in Table II, L_{eq}, L_{Aeq}, L_{eq5124}, the analysis becomes a single-variable regression analysis. For example, the linear regression equation of L_{eq} is

$$PTS_{5124} = b_0 + b_1 L_{eq} + \epsilon \quad (5)$$

where ϵ is the error to be minimized. From Eq. (5), the best fitting regression line, i.e., the values of b_0 and b_1, are determined, and r^2 value and the square of the correlation coefficient are calculated. $r^2 = 1$ indicates a perfect correlation and $r^2 = 0$ indicates no correlation between the metric and NIHL.

Multiple predictor regression models are constructed for the last three metrics in Table II, which has a kurtosis correction term. For example, the regression equation for $L'_{eq} = L_{eq} + \lambda \log_{10}\frac{\beta}{\beta_G}$ becomes

$$PTS_{5124} = b_0 + b_{Leq}L_{eq} + b_{k1}\log_{10}\frac{\beta}{\beta G} + \epsilon. \quad (6)$$

The regression analysis obtains the best values for b_o, b_{Leq}, and b_{k1} that minimizes ϵ. $\lambda = \frac{b_{k1}}{b_{Leq}}$ and corresponding r^2 values are obtained for each metric. The correlation study result is summarized in Table II.

Between the two traditional metrics, L_{Aeq} has a slightly better r^2 value than L_{eq}, which supports the practice of using L_{Aeq} over L_{eq} in noise guidelines. Among the metrics without the correction tern, $L_{eq,5124}$ shows by far the best correlation, which is expected from the cochlea position theory. Kurtosis correction improves correlation of all three metrics L_{eq}, L_{Aeq}, and $L_{eq,5124}$. Overall, $L'_{eq,5124}$ shows the best correlation with the NIHL. The best two metrics are $L'_{eq,5124}$ and $L_{eq,5124}$. The kurtosis correction term does not improve L_{Aeq} and $L_{eq,5124}$ as much as it does for L_{eq}.

Table III shows r^2 values of the kurtosis correction term with L_{eq}, L_{Aeq}, and $L_{eq,5124}$. It is seen that the correction term is least correlated with L_{eq}. This explains why adding the correction term to L_{eq} makes the biggest difference of the performance of the metric.

TABLE III. r^2 values of the correlation between the kurtosis correction term and the basis noise metric. L_{eq} has the smallest r^2 value; thus are least correlated with the correction term. This explains that adding the correction term to L_{eq} has the biggest effect as it is shown in Table II.

	L_{eq}	L_{Aeq}	$L_{eq,5124}$
$\lambda \log_{10}\frac{\beta}{\beta_G}$	0.05	0.11	0.26

Figure 1 shows the scatter plots of the PTS_{5124} values against the metric values with the regressed line. Each point represents the PTS_{5124}-metric pair of the 23 animal groups. Scatter plots are compared for L_{eq} and L'_{Aeq} in Fig. 1(A), for L_{Aeq} and L'_{Aeq} in Fig. 1(B), and for L_{eq} and L'_{Aeq} in Fig. 1(C). It is seen that the correction term improves the correlation for all three metrics.

Although it is the third best metric, L'_{Aeq} has an advantage. Because it is based on L_{Aeq}, the noise metric used in most current noise guidelines, and it can be used with a current noise guideline without any changes by simply adopting L'_{Aeq} in the place of L_{Aeq}. For example, 85-dBA PEL and 3-dB exchange rule in the current NIOSH guideline can be used if they are defined in terms of L'_{Aeq}.

IV. APPLICATION TO HUMAN DATA

The corrected A-weighted SPL developed in this study, L'_{Aeq}, was tested against the human data gathered by Hamernik and his collaborators in China (Zhao *et al.*, 2010). $L_{eq,5124}$ and $L'_{eq,5124}$ could not be tested because the digital noise exposure time histories of the noises were not available to the authors. Among 195 subjects who participated in the survey, 32 subjects were exposed to complex noises of the average kurtosis of 44 for 123 ± 7.1 yr and 163 subjects were exposed to a Gaussian noise ($\beta = 3$) for 12.7 ± 8.4 yr. The adjusted high frequency noise induced hearing loss (AHFNIHL) was used as the NIHL. AHFNIHL is defined as the percentage of population having a higher HTL by 30 dB or more than the 50th percentile of the age and gender matched population found in the ISO standard in Annex B in either ear at 3, 4, or 6 kHz (ISO-1999, 1990). The cumulative noise exposure (CNE) index was used as the noise metric (dose), which is defined:

$$CNE = L_{Aeq,8hr} + 10\log_{10}T\,, \qquad (7)$$

where T is the exposure duration measured in years.

Similar to the procedure adopted in the original study (Zhao *et al.*, 2010), the subjects are separated into 5-dB CNE bins to study the metric–NIHL relationship. In Fig. 2, the solid line with filled diamond symbols shows the relationship of the group exposed to the Gaussian noise, and the dashed-line with filled square symbols shows the relationship of the group exposed to complex noises. The difference between the NIHL values of the two curves associated with the same CNE value can be considered as the additional risk of the complex noise, which is ignored in current noise guidelines. Figure 2 shows that the complex noise induces significantly higher NIHL than the Gaussian noise of the same CNE value.

Zhao *et al.* (2010) developed the kurtosis corrected metric CNE' as follows:

$$CNE' = L_{Aeq,8hr} + \frac{\ln(\beta) + 1.9}{\log(2)}\log_{10}T. \qquad (8)$$

The correction in Eq. (8) was determined so that CNE'-NIHL relationship of the group exposed to complex noises ($\beta = 44$) is best matched with CNE-NIHL relationship of the group

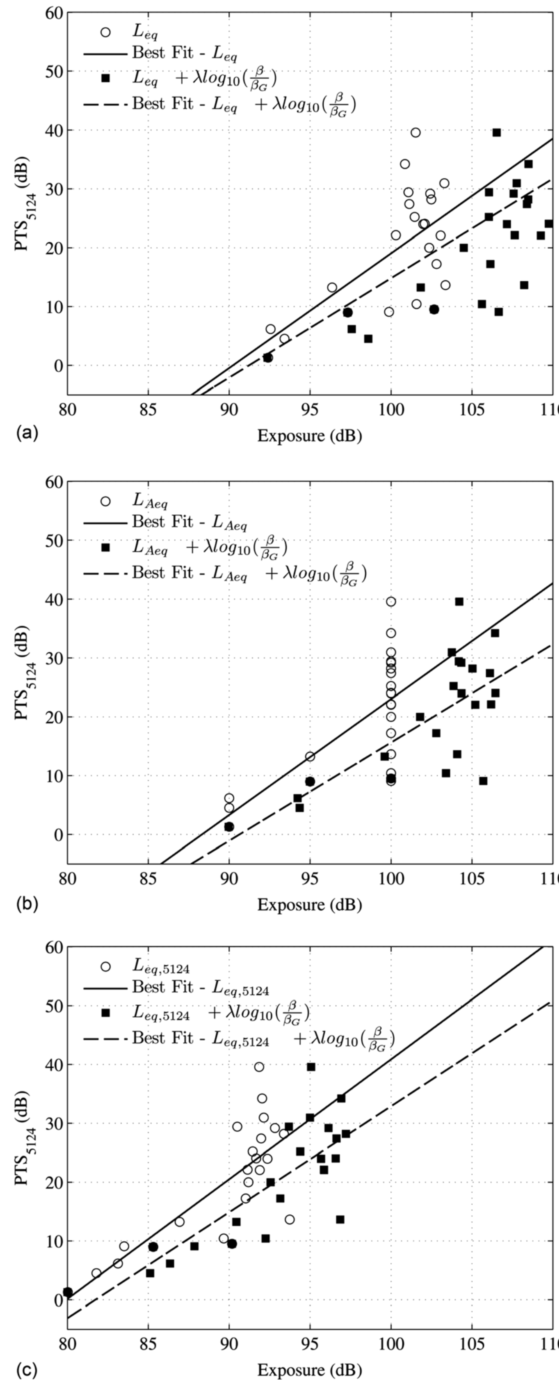

FIG. 1. Scatter plots of the PTS_{5124} values against the metric values with the regressed lines. Each point represents the pair of the average PTS_{5124} of the chinchillas in the group exposed to one specific type of noise and the metric calculated for the noise. (A) against L_{eq} and L'_{eq}, (B) against L_{Aeq} and L'_{Aeq}, and (C) against $L_{eq,5124}$ and $L'_{eq,5124}$. It is seen that adding the kurtosis correction term improves the correlation between the metric and PTS_{5124}.

exposed to the Gaussian noise ($\beta = 44$) and CNE' reduces to CNE for a Gaussian noise ($\beta = 3$). The correction form in Eq. (8) was determined based on only one set of data; therefore generality of the correction is not known.

The correction scheme we developed [see Eq. (3)] is independent of the exposure time length; therefore, CNE', the kurtosis-corrected CNE, according to our scheme is defined as follows:

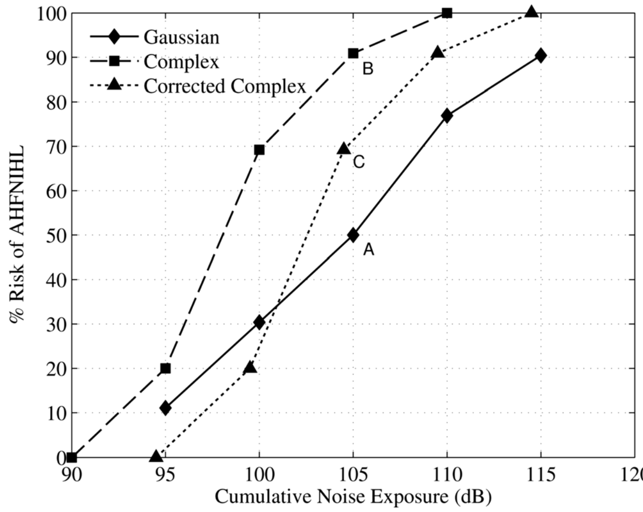

FIG. 2. Effect of kurtosis correction on the measured human NIHL data. AHFNIHL is percentage of the subjects having a higher HTL by 30 dB or more than the control group. Solid line with filled diamond symbol represents the CNE-NIHL relationship of the group exposed to Gaussian noises, dashed line filled square symbol represents the CNE-NIHL relationship of the group exposed to complex noise, and dotted line with filled triangle symbol represents (kurtosis corrected CNE) CNE′-NIHL relationship of the group exposed to complex noises. CNE′-NIHL curve of the complex noise becomes much closer to the CNE-NIHL curve of the Gaussian noise, which the kurtosis correction reduces underestimation of the risk of complex noises.

$$CNE' = L'_{Aeq,8hr} + 10\log_{10}T = L_{Aeq,8hr} + \lambda\log_{10}\frac{\beta}{\beta G} + 10\log_{10}T = CNE + \lambda\log_{10}\frac{\beta}{\beta_G} \quad (9)$$

where $\lambda = 4.02$ as it was identified for L'_{Aeq} previously. As the complex noises in this study have the average kurtosis value $\beta = 44$ and $CNE' = CNE + 4.69$. The relationship between the AHFNIHL and CNE' of the complex noises group is shown as the dotted line with filled triangle symbols in Fig. 2. Improvement due to kurtosis correction term is readily apparent. The metric–NIHL relationships of the Gaussian and complex noises have become much closer to each other, which imply that the corrected metric CNE' will reduce underestimation of the risk of exposure to complex noises. For example, without the kurtosis correction, the AHFNIHL associated with a noise of $CNE = 105$ is 50% if the noise is Gaussian (point A in Fig. 2) or 90% if the noise is a complex noise of $\beta = 44$ (point B). With the kurtosis correction, the AHFNIHL associated with a noise of CNE′ = 105 is 50% if the noise is Gaussian (point A) and 70% if the noise is a complex noise of $\beta = 44$ (point C). Similar improvement is observed at other levels. This suggests that the use of a kurtosis corrected metric will enable to assess the risk of complex noises more accurately. It is noted that the above demonstration should be interpreted qualitatively because the model developed based on chinchilla data was applied to human data without any adjustments for effects of different definitions in NIHL (PTS_{5124} vs PTS_{1234}; short-term cute shorter exposure vs long-term exposure). More studies will be necessary to realize the potential benefit of adopting a kurtosis corrected noise metric.

V. DISCUSSIONS

A. Basic hypotheses used in development of new noise metrics

The approach adopted in this work is developing new noise metrics by using chinchilla noise exposure data and then applying them to assess the risk of human noise exposure. It takes advantage of abundant, directly measured noise exposure study data. The approach obviously involves various errors because it uses the chinchilla data for human application. Besides the expected differences in the DRR of the human and chinchilla, definitions of the dose and response (NIHL) are different. For example, NIOSH guideline defines *dose* as 8-h exposure during extended durations of exposure, while chinchillas were exposed to 5 days continuous exposures; response in NIOSH guideline is defined as having 25-dB or higher HTL averaged for 1, 2, 3, and 4 kHz, while it is defined as the PTS averaged for 0.5, 1, 2, and 4 kHz in chinchillas. Therefore, the approach in this work implicitly adopts the following hypotheses:

(1) Human and chinchillas have similar DRR in a relative sense. That is, if a given noise causes higher NIHL than the other noise in chinchillas, the same will occur in human.
(2) Long- and short-term exposures have similar DRR in a relative sense. That is, if one noise causes higher NIHL than the other noise in a short-term exposure, the same will occur in a long-term exposure also.

The above hypotheses are plausible when the similarity of the auditory systems of human and chinchillas is considered; however, empirical validation is still needed. The first hypothesis may be validated by using animal tests, for example by showing that the noise metric developed from chinchilla data applies to other species such as guinea pigs. The second hypothesis will have to be validated by applying the new noise metric to a sufficient number of human exposure study data. Future human studies for this purpose will have to record the time history of the noise to permit kurtosis correction. Such validation will still be indirect and limited because of the nature of the human data. Workers' exposures will be inevitably cross sectional and not longitudinal in their careers (e.g., 30 yr). Furthermore, non-occupational noise exposure, individual health effects, ototoxic chemicals, and drugs are uncontrolled factors that will confound such analyses. For example, it is highly unlikely that the noise to which workers are exposed will remain the same over a long duration; there are many uncontrollable factors such as exposure to recreational noises or effects of other illnesses.

B. Reference kurtosis β_G

The basic form of the new noise metric, $L'_{eq} = L_{eq} + \lambda\log_{10}\frac{\beta}{\beta_G}$, was designed so that Gaussian noises are the reference noise exposure. Current noise guidelines may be considered as the result of empirical data accumulated for a long period of time for *most common* occupational noise environments, which may have higher kurtosis than β_G. In this case, using β_G as the reference kurtosis in the correction may result in over-evaluation of the risk of complex noises.

A better reference kurtosis may be identified by surveying "typical" occupational noise environments.

C. Modification of $L'_{eq,5124}$ to utilize it in human guidelines

$L'_{eq,5124}$ was adopted because PTS and NIHL of chinchillas were measured at 0.5, 1, 2, and 4 kHz, not at 1, 2, 3, and 4 kHz that most human guidelines adopt to define NIHL. Therefore, $L'_{eq,1234}$ has to be used for human application instead of $L'_{eq,5124}$, while using the same λ value identified for $L'_{eq,5124}$ from the chinchilla data. The effects of this simplification will have to be further investigated.

D. Potential application of the new noise metrics to human guidelines

Among the three best noise metrics, L'_{Aeq} is the easiest to apply in human guidelines as it was mentioned, because adopting it in a noise guideline does not require any other changes. Some manipulation is necessary to use L'_{Aeq} because it does not represent the overall SPL. Because using $L'_{eq,1234}$ can be viewed as a type of weighting, one option is using $L''_{eq,1234}$, a scaled $L'_{eq,1234}$ defined as follows:

$$\begin{aligned} L''_{eq,1234} &= L'_{eq,1234} + (L_{eqA,G} - L_{eq,1234,G}) \\ &= L''_{eq1234} + 9.2 \end{aligned} \quad (10)$$

where $L_{eqA,G} - L_{eq},_{1234,G}$ is the difference of the A-weighted SPL and $L_{eq,1234}$ of the Gaussian-white noise, which is 9.2-dB, independent of the level of the noise. If the noise is Gaussian-white noise, $L'_{eq,1234} = L_{eq,1234,G}$; therefore, $L''_{eq,5124}$ reduces to L_{Aeq}. $L''_{eq,1234}$ defined in Eq. (10) can be used in place of L_{Aeq} in the noise guideline.

VI. CONCLUSIONS

It has been widely regarded that current noise guidelines underestimate risk of complex noises because they employ A-weighted equivalent SPL (L_{Aeq}) as the noise metric which ignores the effect of temporal characteristics of the noise (NIOSH, 1998). To address this problem, a new form of noise metric with a temporal correction term was designed as $L'_{eq} = L_{eq} + \lambda \log_{10} \frac{\beta}{\beta G}$, where β and β_G are kurtosis values of the given and Gaussian noises. This basic form was designed so that no correction is made for Gaussian noises, and higher corrections are made for more kurtosis complex noises. Six noise metrics including four new metrics developed by varying the basic form were evaluated utilizing chinchilla noise exposure test data for their correlations with the NIHL in chinchillas. NIHL was defined as the average of the PTS at 0.5, 1, 2, and 4 kHz to make it similar to the definition used in human guidelines. Evaluation showed that the kurtosis correction term generally improves correlations of the metric with NIHL. The metric $L'_{eq,5124}$ (kurtosis corrected $L_{eq,5124}$) showed the highest correlation with NIHL, where $L_{eq,5124}$ is the average of L_{eq} of 0.5, 1, 2, and 4 kHz components of the noise, followed by $L_{eq,5124}$ and L'_{Aeq} (kurtosis corrected L_{Aeq}). The r^2 values (square of the correlation coefficient) of the correlations of these three best metrics were 0.67, 0.61, and 0.54, respectively, compared to 0.46 of the current noise metric L_{Aeq}. L'_{Aeq} was applied to a set of human noise exposure data obtained from two groups, respectively, exposed to a Gaussian noise environment and a complex noise environment, which showed a good potential of the approach proposed in this work.

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

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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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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:

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

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 (β) + 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 $L_{Aeq,8h}$, 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.

Acknowledgments

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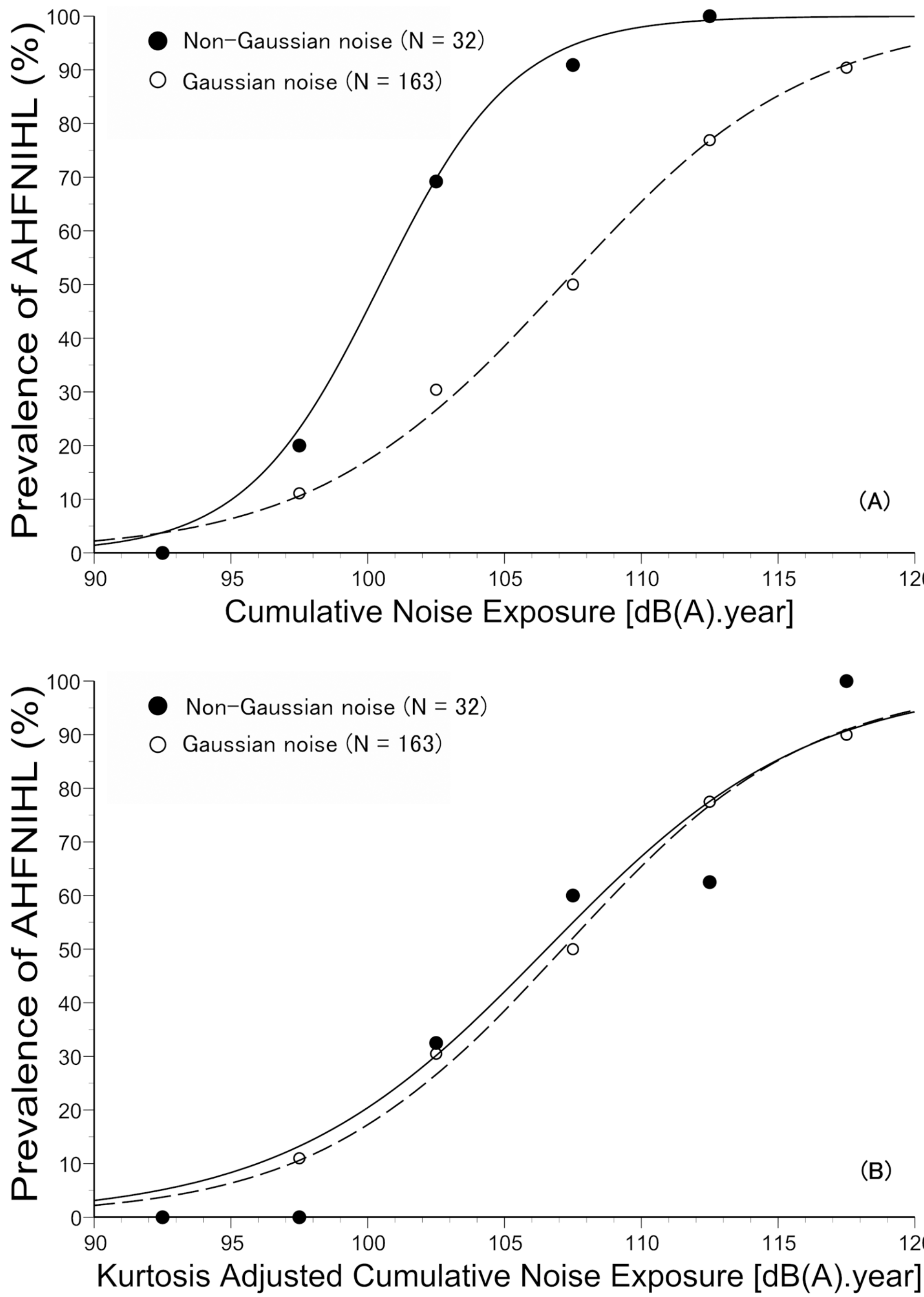

Figure 1.

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.

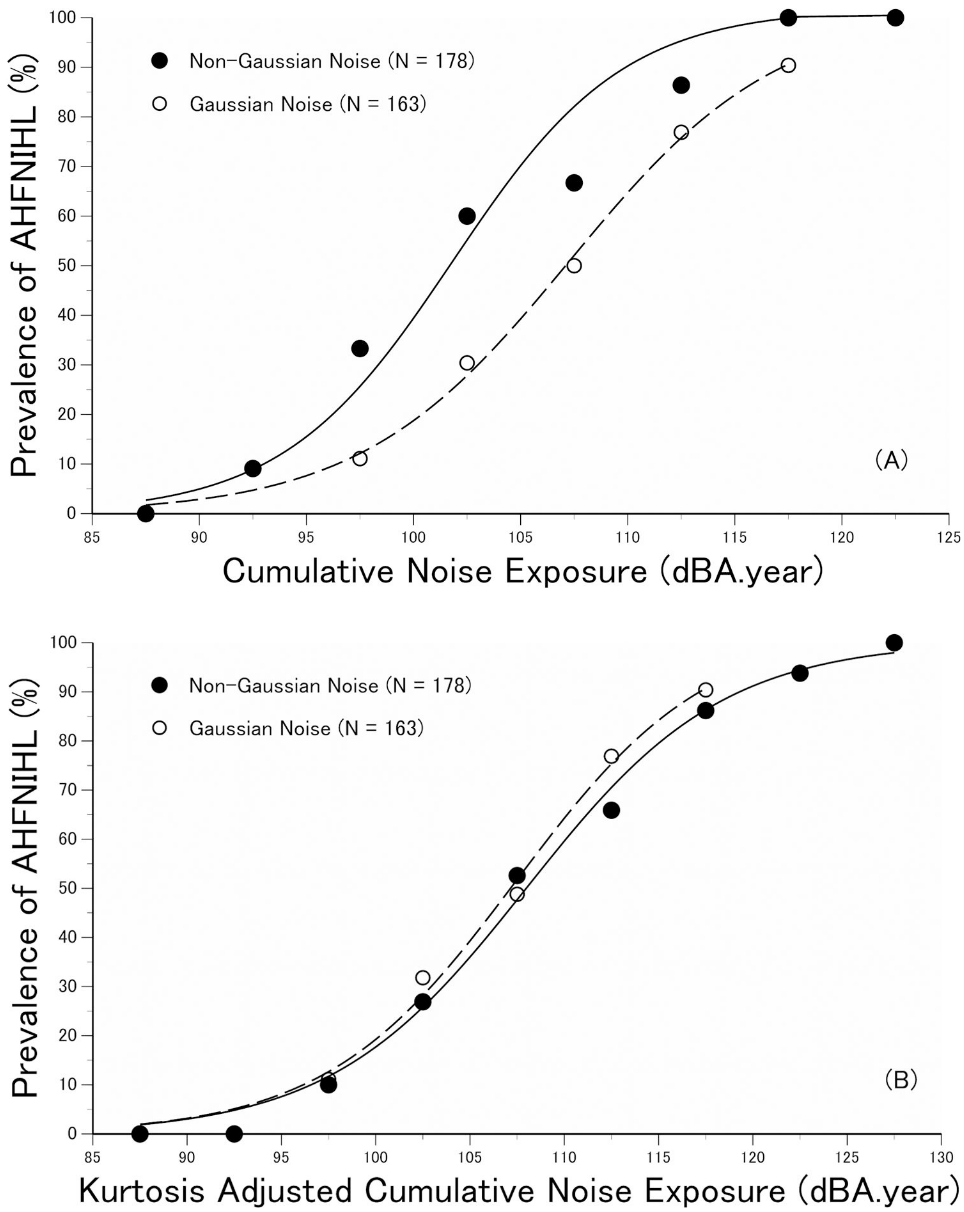

Figure 2.

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.

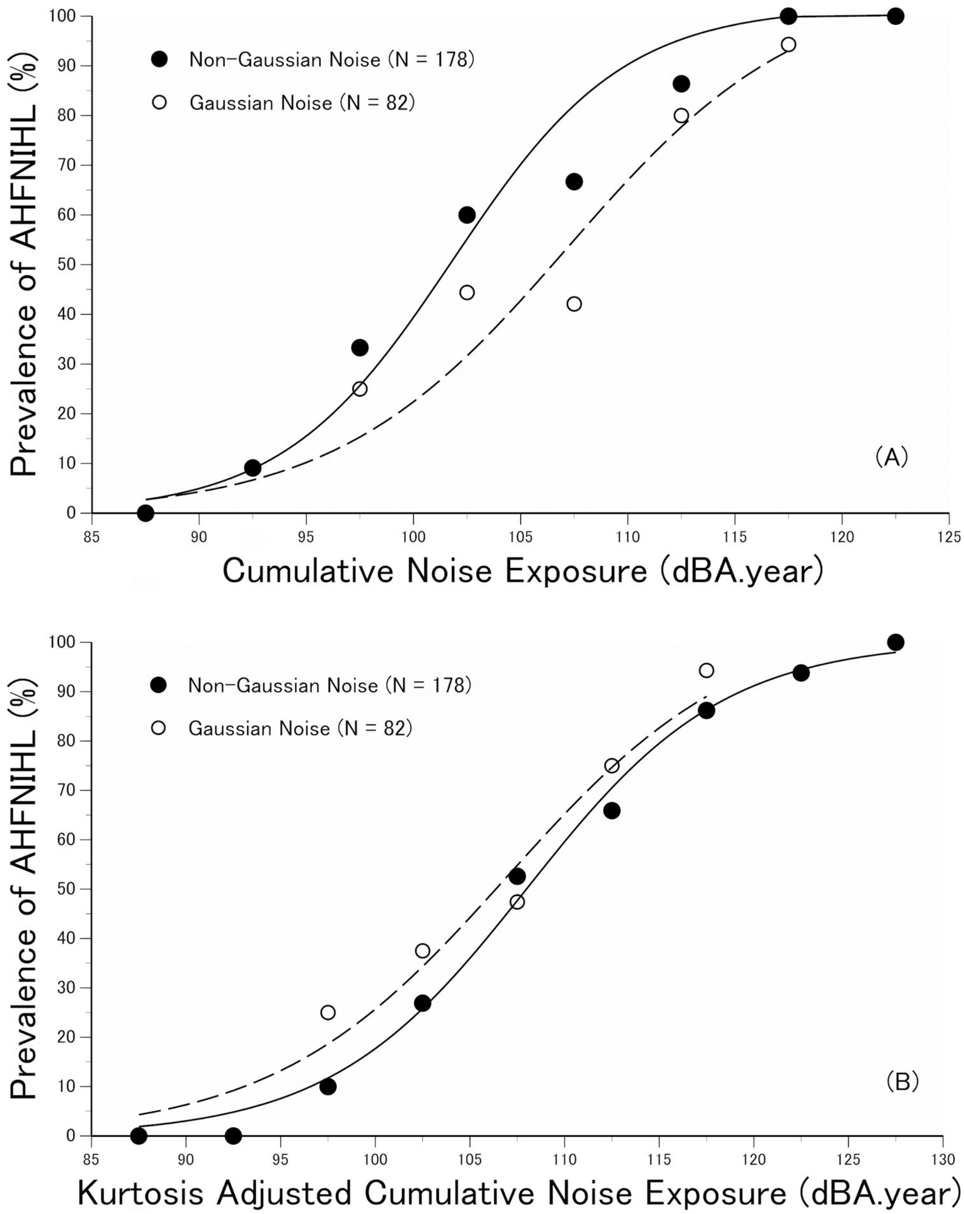

Figure 3.

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.

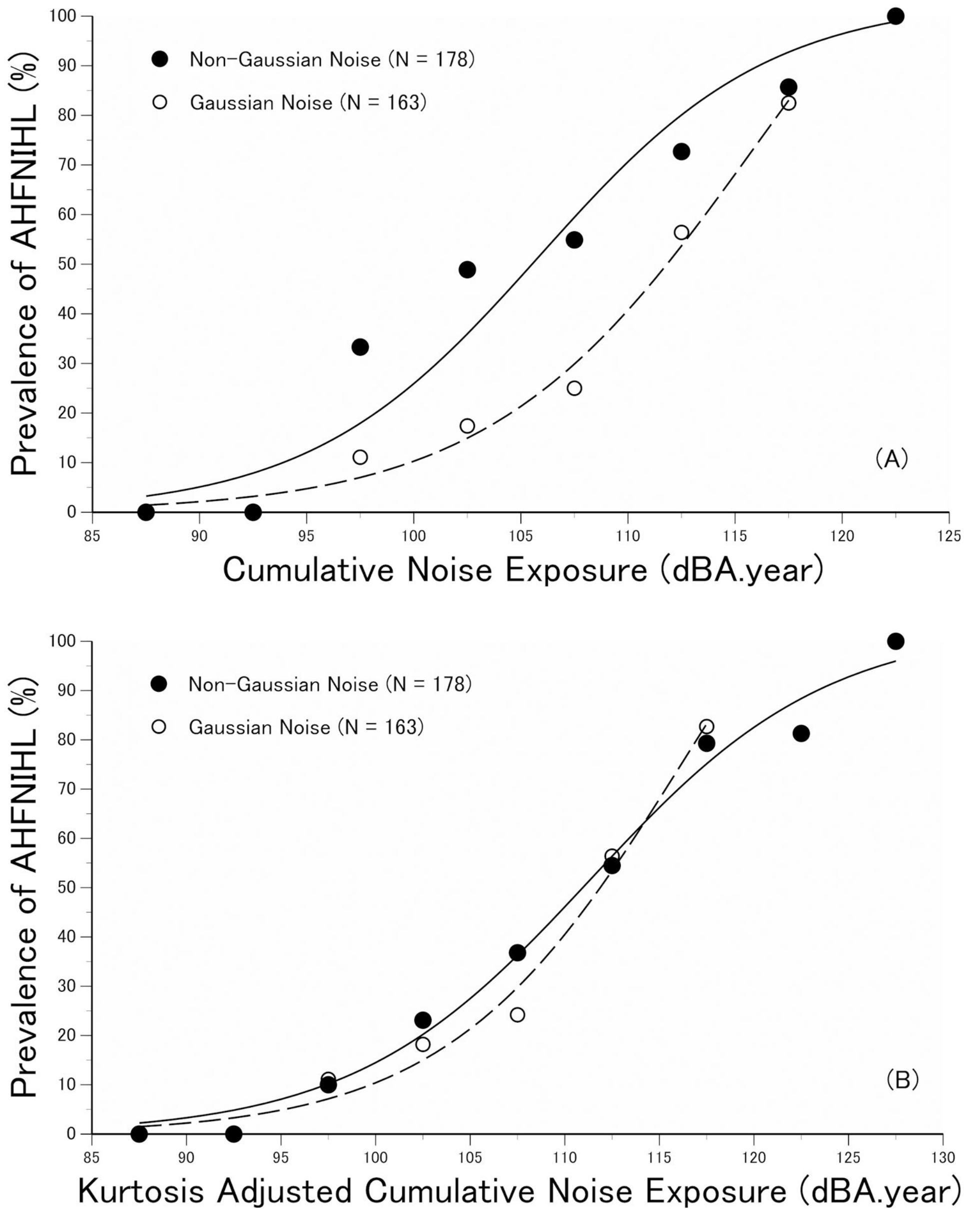

Figure 4.

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

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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.

The Effect of Hearing Protection on Kurtosis

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The Effect of Hearing Protection on Kurtosis

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ABSTRACT
Hearing loss in the construction and mining sectors has about a 25% prevalence rate based upon published NIOSH research. Dunn et al. demonstrated that impact noise was more hazardous to the hearing of chinchillas than an equal level (Leq) continuous noise [1]. Zhao et al. demonstrated that human workers exposed to high kurtosis (4th standardized moment) noise accumulated hearing loss at faster rates than those workers exposed to lower kurtosis values [2]. Operation of machinery can be particularly hazardous when that noise contains significant peaks of high levels exceeding the average levels. Jackhammer noise is one example of a noise exposure that has both a high exposure level (107 dB SPL) and a high kurtosis (15 to 17). This study evaluated six hearing protection devices fitted on an acoustic test fixture. The average reductions of jackhammer noise level for the HPDs was between 21 and 42 dB. For traditional passive HPDs (muffs and plugs), the kurtosis values were reduced to between 3 and 12. For a filter-style earplug in the open condition, the kurtosis value was reduced from 16 to 12. For the earmuff, the kurtosis value was reduced from 15 to 3.

Disclaimer: *The findings and conclusions in this report are those of the author and do not represent any official policy of the Centers for Disease Control and Prevention or the National Institute for Occupational Safety and Health. Mention of company names and products does not constitute endorsement by the CDC or NIOSH.*

Keywords: hearing protection devices, NIHL, kurtosis
I-INCE Classification of Subject Number: 36

1. INTRODUCTION

In road construction, jackhammers are commonly used to remove material in preparation for laying new road surface. The peak, impulse-noise levels of a jackhammer can exceed 120 dB SPL at the operator's ears or 100 dB SPL a few meters in front of the operator. Depending upon position where noise is sampled, the equivalent A-weighted levels can range from 90 to 110 dB(A) SPL. The permissible exposure times for such high levels would be 2 hours to less than 2 minutes based upon an 85-dB(A) limit for 8 hours and a 3-dB exchange rate [3].

In the ANSI S3.44 standard for estimating occupational noise exposure, a 5-dB allowance can added to exposures that are primarily impulsive [4]. Dunn et al. found that

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chinchillas exposed to equivalent levels of continuous and impulsive noise exhibited greater hearing loss for impulsive exposures [1]. Zhao et al. found a similar increased risk for impulsive noise exposures among Chinese workers [2]. Exposure to high-level impulsive noise present a greater potential to produce hearing loss among workers.

In 2010, researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted measurements of several models of jackhammers to identify noise sources and to evaluate the performance of possible noise controls. Five hearing protection devices (HPDs) were tested with an acoustic test fixture (ATF) to evaluate performance in high-level impulsive noise. Methods from the ANSI S12.42 standard [5] were applied to estimate the insertion loss of the HPDs and determine allowable exposure times when protection is worn. Recordings of the occluded and unoccluded ATF were used to estimate the kurtosis in both conditions and the potential change in the allowable exposure times.

2. METHODS

2.1 Jackhammer Loaded Testing

Measurements of a Makita model HM1810 jackhammer with a Bosch model HS2163 narrow chisel were conducted at the NIOSH Pittsburgh Mining Research Division's large hemi-anechoic chamber in January 2011. The jackhammer was operated fully loaded on a test stand constructed from 20x26x6 inch thick concrete blocks having a compressive strength of 5000 psi (Quality Concrete, Pittsburgh, PA). The concrete had a nominal curing time of 28 days. The concrete blocks were stacked in a 3 by 3 grid as shown in Figure 1. The concrete test stand was built over a grid of rubber acoustic ballistic tiles to protect the floor and damp vibrations (New Century Northwest LLC, Eugene, OR). The 24x24x1.5 inch rubber tiles weighed about 29 lbs each and had a stiffness of 70 Shore A. During testing, the jackhammer operator stood on top of the test stand and chipped through the concrete of the first layer of concrete blocks. The operator was instructed to allow the weight of the jackhammer to do most of the downward work and to apply only downward force on the jackhammer to control the tool [6].

2.2 Hearing Protector Testing

Five models of hearing protection devices (Bilsom 707 Impact II® earmuff, Etymotic Research Inc. Electronic BlastPLG® EB1 earplug, 3M™ Combat Arms™ single tip earplug, 3M™ E-A-R™ Express™ Pod Plugs™, and 3M™ E-A-R™ Classic™ foam earplug) were evaluated with the jackhammer using an ATF. The Bilsom 707 earmuff and EB1 earplug have been discontinued. The ATF was built by the French-German Research Institute of Saint Louis and had a single GRAS 60711 coupler fitted with a ¼” Brüel and Kjær 4135 pressure microphone with Head Acoustics HMS II pinna and 10 mm ear canal. Each hearing protection device was fitted on the fixture. A pair of occluded and unoccluded measurements were made with the jackhammer in nominally the same location to yield approximately the same levels. One transit of the jackhammer through the concrete blocks was made. The hearing protection was removed, the jackhammer moved to the side and another transit was made. Recordings were made with a National Instruments PXI-4462 card, ±42V range, and 24-bit resolution for 5 seconds. The first 2.5 seconds of the recordings were used in the analysis because not every transit of the jackhammer lasted the entire 5 seconds.

Figure 1. Concrete blocks, chisel close-up, and jackhammer operator.

2.3 Impulse Spectral Insertion Loss

The ANSI S12.42-2010 standard specifies that an impulse source be used to estimate the complex acoustic transfer function for the unoccluded condition between the field probe microphone and the acoustic test fixture [5]. The source is assumed to remain in a fixed location relative to the microphones. With the jackhammer, the complex, transfer function changes slightly whenever the source is moved, thus precluding the strict application of this method. Instead, a spectral transfer function is determined for the unoccluded condition and is used to estimate the unoccluded ear spectral levels of the ATF when it is occluded.

Fackler et al. [7] proposed a modification of IPIL that maintained the spectral information included in the complex transfer function and permitted a comparison to real ear attenuation at threshold (REAT) measurements of HPDs. However, the complex transfer function used to estimate IPIL and impulse spectral insertion loss (ISIL) is a function of the distance from the source to the receivers. For each transit of the jackhammer, the impulse source is moved in all three directions (right/left, front/back and up/down). Although the spatial distances are small and likely inconsequential, the complex transfer function does not remain constant. The ISIL is determined with a transfer function computed with the output levels of one-third octave band filters from the field probe and the unoccluded ear of the ATF,

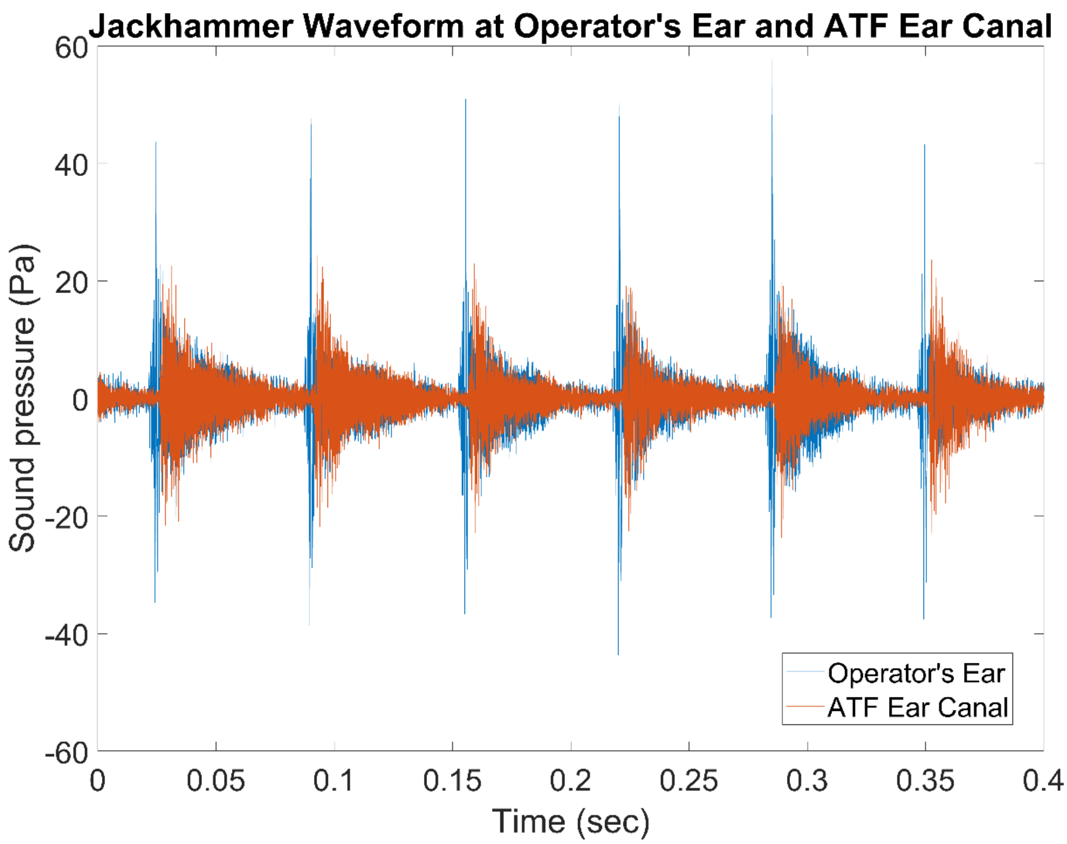
$H_{\mathrm{FF,ATF},f} = H_{\mathrm{TOB},f}\left(p_{\mathrm{FF}}(t)\right) - H_{\mathrm{TOB},f}\left(p_{\mathrm{ATF,open}}(t)\right)$, where $H_{\mathrm{TOB},f}$ is the third octave band filter for the center frequency, f, and $H_{\mathrm{FF,ATF},f}$ is the transfer function between the field probe microphone and the unoccluded ear of the ATF [8]. The phase of the transfer function is not used.

2.4 Kurtosis analysis

Lei et al. [9] proposed using kurtosis, $\beta = \left[\frac{E[(x-\mu)^4]}{(E[(x-\mu)^2])^2}\right]$, to characterize the impulsive character of a noise exposure amplitude. In evaluating workers' noise exposures, Zhao et al. [2] used cumulative noise exposure to reconcile impulsive and non-impulsive exposures, CNE $= L_{\mathrm{Aeq,8h}} + \mathrm{K}[\log\ T/\log 2]$, where T is the exposure duration in years, $\mathrm{K} = \ln(\beta) + 1.9$, and β is the kurtosis. This form worked well when the exposures were long term, but it is time dependent and may not be particularly useful when analyzing exposure recordings that last only seconds. Goley et al. [10] proposed a kurtosis correction to the equivalent noise level that was not dependent upon the length of a person's exposure time, $L'_{\mathrm{eq}} = L_{\mathrm{eq}} + \lambda \log_{10}\frac{\beta}{\beta_G}$, where λ is 4.02, β is the kurtosis of the noise sample, and $\beta_G = 3$ is the kurtosis of a normal distribution. This correction was calculated on the first 2.5 seconds of the jackhammer recordings and applied to the equivalent A-weighted levels, L_{Aeq}.

3. RESULTS

Impulses from the jackhammer are shown in Figure 1. The blue trace shows the microphone at the operator's ear and the orange trace is the ear canal microphone of the ATF. The operator levels in this short sample range from about 125 to 130 dB peak SPL. The ATF levels range from about 120 to 123 dB. The signal level at the ATF change as the jackhammer moves over the concrete blocks, closer and further away. The cycle rate of the jackhammer is about 15 strikes per second and the ring of the jackhammer impact decays significantly within each cycle.



The overall A-weighted noise levels calculated from the one-third octave band data from 100 to 10000 Hz are reported in Table *1*. The levels at field probe microphone, 17 cm from the ATF right ear, were between 105 and 108 dBA. The occluded levels varied from 66 dB for the Express Pod earplug to 85 dB for the Combat Arms earplug in the open filter condition. The kurtosis values for the unoccluded ATF conditions ranged between 14.8 and 17.2. When the hearing protector is applied, the kurtosis is reduced significantly. The A-weighted attenuations ranged between 21 and 42 dB for the open filter Combat Arms earplug and the Express Pod Plugs, respectively. The other protectors yielded between 34 and 38 dB attenuation.

Table 1. The average L_{Aeq} levels, kurtosis values, and A-weighted Attenuation for the six hearing protector unoccluded and occluded conditions.

Hearing Protector	Unoccluded Condition		Occluded Condition		Attenuation A-weight (dB)
	L_{Aeq} (dB)	Kurtosis, β	L_{Aeq} (dB)	Kurtosis, β	
Impact 707	107.5 ± 3.0	15.0 ± 3.4	74.0 ± 3.8	2.6 ± 0.6	33.5 ± 4.6
EB-1	107.8 ± 2.4	14.8 ± 2.1	73.8 ± 3.0	6.2 ± 1.4	34.0 ± 1.1
CAE Closed	108.3 ± 4.4	15.4 ± 2.8	73.2 ± 2.4	7.1 ± 3.0	35.1 ± 3.6
CAE Open	105.8 ± 4.0	15.5 ± 2.9	84.8 ± 2.6	12.1 ± 3.5	21.0 ± 1.6
Pod	108.5 ± 4.3	17.2 ± 7.1	66.8 ± 4.1	6.6 ± 3.4	41.7 ± 5.5
Classic	108.9 ± 2.6	17.0 ± 4.6	70.7 ± 5.7	10.6 ± 6.6	38.2 ± 4.7

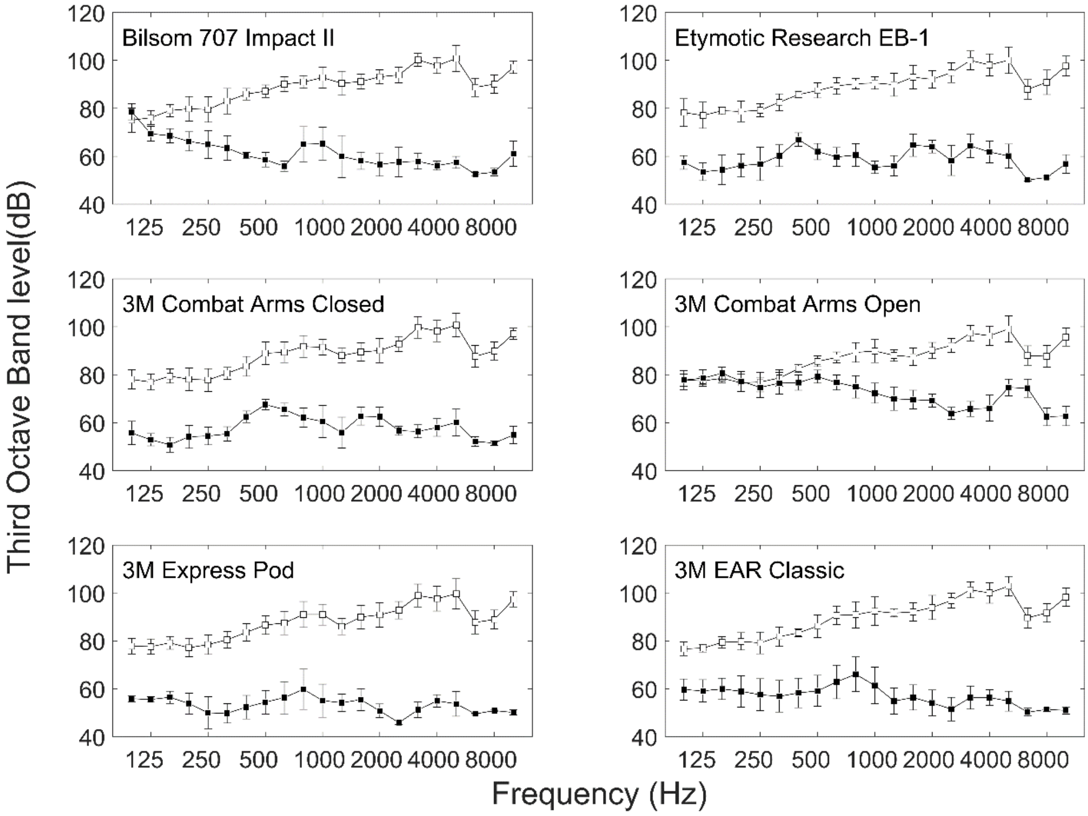


Figure 2. The spectra of the unoccluded and occluded recordings of the ATF with different hearing protectors. The unoccluded levels are shown as open symbols. The occluded levels are shown as solid black symbols. The error bars represent one standard deviation.

In Figure 2, the one-third octave band spectrum levels are presented for the unoccluded (open symbols) and occluded (closed symbols) conditions. The dominant region of the jackhammer noise is in the 3000 to 6000 Hz region. For the Bilsom 707 Impact II earmuff, the attenuation is nearly zero at the lowest frequencies. Similarly, the 3M Combat Arms earplug in the open filter condition has little attenuation for frequencies below 500 Hz. The Etymotic Research EB1 and the 3M Combat Arms closed filter condition have nearly the same occluded spectrum. This finding is not surprising considering that the design of the three flanges is nearly identical between the two products. The Express Pod and Classic earplugs also have similar occluded levels. The Express Pod earplugs fit completely within the ear canals of the fixture while about 60% of the Classic earplugs could be inserted into the ear canal of the fixture.

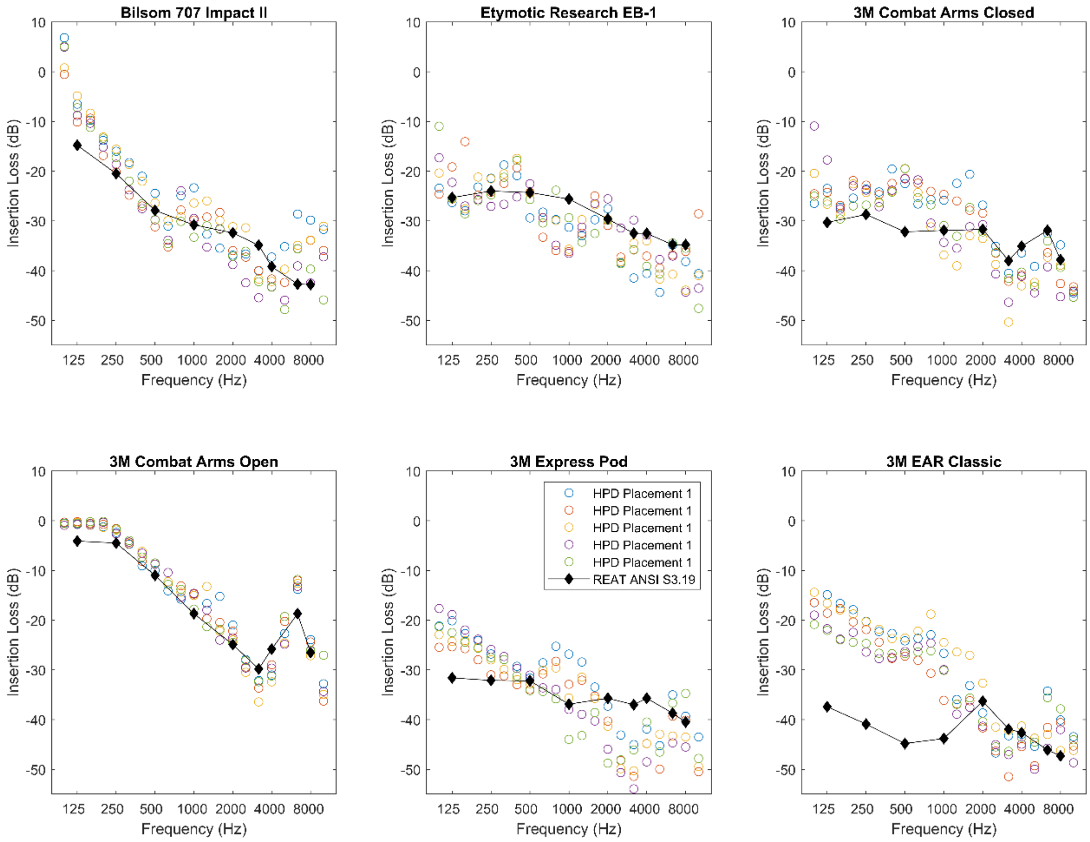


Figure 3. Comparison of ISIL results for each protector model and sample fitting with the Manufacturer's experimenter-fit REAT data.

In Figure 3, the ISIL results are compared to the manufacturers' published REAT data. The five fittings of the HPDs on the ATF are indicated with different colored circle symbols and the REAT are displayed as black diamonds connected with a solid line. The agreement of the ISIL with REAT is good except for the Express Pod and Classic earplugs. The results between 2 and 6 kHz on the ATF overestimate the REAT data for the Express Pod earplug. The REAT data from 125 to 1000 Hz overestimate the ATF data for the Classic earplug. Two competing factors might explain these differences for the Express Pod and Classic earplugs. Both plugs create the seal to the canal of the ATF with a foam material. The entire Express Pod plug fits into the canal and may provide greater attenuation than is observed in real persons due to the bone conduction that affects 2 to 4 kHz REAT data. The Classic plug is affected by the short ear canal of the ATF and fails to provide significant attenuation below 1000 Hz.

3.1 Effects of Kurtosis on Exposure Time

Kurtosis correction was calculated for all of the protected and unprotected conditions as shown in Table 2. The kurtosis adjustment, $\Delta L_\beta = \lambda \log_{10}\left(\frac{\beta}{\beta_G}\right)$, for the unoccluded condition was nominally a 3-dB increase. The occluded kurtosis corrections ranged from ΔL_β = -0.3 to 2.3 dB. The earmuff had the least kurtosis correction, -0.3 dB, and the open-filter Combat Arms earplug had largest correction, 2.3 dB. The other hearing protectors had about a 1 to 2 dB increase in the adjusted exposure level. The relative exposure time can be calculated, $T_{L,\beta}/T_L = 2^{\Delta L_\beta/3}$, where 3 is the exchange rate, $T_{L,\beta}$ and T_L are the exposure times for the kurtosis-adjusted and unadjusted exposure levels. For the Combat Arms earplug, the allowable exposure time would be reduced by about 60% when kurtosis is included.

Table 2. The average unprotected and protected L_{Aeq} levels, kurtosis correction levels and combined levels for the six hearing protector conditions.

Hearing Protector	Occluded Conditions			Unoccluded Conditions		
	L_{Aeq} (dB)	β - Adjusted Level (dB)	Combined Level (dB)	L_{Aeq} (dB)	β - Adjusted Level (dB)	Combined Level (dB)
Impact 707	74.0	-0.3	73.7	107.5	2.8	110.3
EB1 (Off)	73.8	1.2	75.0	107.8	2.8	110.6
CAE Closed	73.2	1.4	74.5	108.3	2.8	111.1
CAE Open	84.8	2.3	87.1	105.8	2.8	108.7
Pod	66.8	1.2	68.0	108.5	2.9	111.4
Classic	70.7	2.2	73.0	108.9	3.3	112.3

4. DISCUSSION

The kurtosis adjustment was dependent upon the protector more strongly than was expected. Before this investigation, the author would have suggested that the protector with the greatest attenuation ought to have the greatest effect on kurtosis. However in this case, the earmuff yielded the greatest reduction in the kurtosis adjustment. This effect may be explained by the greater attenuation of the high frequency noise relative to the low frequency noise provided by the earmuff. Impact and impulse noises tend to have sharp transitions from low amplitudes to high amplitudes (e.g. a gunshot, a hammer strike). Preferential filtering of high frequency noises by earmuffs should smooth out the transients more so than a flat attenuation spectrum that will uniformly attenuate all of the frequency content.

A second consideration for hearing loss prevention is not so much the added effect on the exposure levels caused by kurtosis, but rather the effectiveness of correct use of hearing protection. Without the kurtosis adjustment, all of the protectors reduced the jackhammer noise to below 85 dBA, the NIOSH REL. The Express Pod earplug had the lowest occluded exposure level as measured on the ATF. The Classic earplug provided the next lowest occluded exposure level. The additional length of the ear canal provided greater contact surface allowing the entire body of the foam earplug to be in contact with the ear canal walls in subsequent versions of the ISL acoustic test fixture and the GRAS 45 CB test fixture [11, 12, 13]. Related to hearing loss prevention, the proper fitting of an earplug in a worker’s ear canal will have a far more significant reduction of the hazardous noise than worrying about whether the kurtosis is better reduced by one type of protector or another.

The Combat Arms open filter condition earplug might not be recommended for this particular noise exposure. Berger and Hamery [14] examined the response of the Combat Arms earplug in response to a range of impulse noise levels, 110 to 190 dB peak SPL. At the lowest level, the attenuation of the filter is minimally effective. The filter relies upon the pressure differential on either side of the filter (unoccluded to occluded) to change the viscous boundary layer in a nonlinear manner. At the jackhammer levels of about 110 dB SPL, the attenuation would be expected to be minimal. Thus, the open filter condition is an application of the wrong hearing protection device for the exposure. Murphy et al [15] tested an advanced hearing protection device with a group of workers at a metal fabrication stamping plant. This product also used a filter inserted into the sound bore of a semi-custom earplug. Many workers returned the semicustom earplugs and reverted to the foam earplugs that they had been accustomed to because the stamping noise transmitted by the semi-custom earplugs was much louder than they were used to experiencing. They preferred the earplugs that gave higher levels of attenuation.

5. CONCLUSIONS

The protection afforded by a properly fit HPD was between 20 and 42 dB. For all of the protectors, the occluded levels before adjusting for kurtosis were below the 85 dB(A) NIOSH permissible exposure level. The Combat Arms earplug with the filter open was close to the 85 dB(A) PEL, and when kurtosis was accounted for, the adjusted level was 87 dB(A). For the other HPDs, the protected levels were at or below 75 dB(A) with and without kurtosis adjustment. The kurtosis adjustment increased the exposure levels slightly, which translated to a reduced exposure time. Hearing protection provided a far greater reduction in exposure time. As always, proper fitting and consistent use of hearing protection when in hazardous noise should be emphasized.

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OPEN

New Metrics Needed in the Evaluation of Hearing Hazard Associated With Industrial Noise Exposure

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Objectives: To evaluate (1) the accuracy of the International Organization for Standardization (ISO) standard ISO 1999 [(2013), International Organization for Standardization, Geneva, Switzerland] predictions of noise-induced permanent threshold shift (NIPTS) in workers exposed to various types of high-intensity noise levels, and (2) the role of the kurtosis metric in assessing noise-induced hearing loss (NIHL).

Design: Audiometric and shift-long noise exposure data were acquired from a population (N = 2,333) of screened workers from 34 industries in China. The entire cohort was exclusively divided into subgroups based on four noise exposure levels ($85 \le L_{Aeq.8h} < 88$, $88 \le L_{Aeq.8h} < 91$, $91 \le L_{Aeq.8h} < 94$, and $94 \le L_{Aeq.8h} \le 100$ dBA), two exposure durations ($D \le 10$ years and $D > 10$ years), and four kurtosis categories (Gaussian, low-, medium-, and high-kurtosis). Predicted NIPTS was calculated using the ISO 1999 model for each participant and the actual measured NIPTS was corrected for age and sex also using ISO 1999. The prediction accuracy of the ISO 1999 model was evaluated by comparing the NIPTS predicted by ISO 1999 with the actual NIPTS. The relation between kurtosis and NIPTS was also investigated.

Results: Overall, using the average NIPTS value across the four audiometric test frequencies (2, 3, 4, and 6 kHz), the ISO 1999 predictions significantly ($p < 0.001$) underestimated the NIPTS by 7.5 dB on average in participants exposed to Gaussian noise and by 13.6 dB on average in participants exposed to non-Gaussian noise with high kurtosis. The extent of the underestimation of NIPTS by ISO 1999 increased with an increase in noise kurtosis value. For a fixed range of noise exposure level and duration, the actual measured NIPTS increased as the kurtosis of the noise increased. The noise with kurtosis greater than 75 produced the highest NIPTS.

Conclusions: The applicability of the ISO 1999 prediction model to different types of noise exposures needs to be carefully reexamined. A better understanding of the role of the kurtosis metric in NIHL may lead to its incorporation into a new and more accurate model of hearing loss due to noise exposure.

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Key words: Occupational noise exposure, ISO 1999 model, Gaussian noise, Non-Gaussian noise, Kurtosis, Noise-induced permanent threshold shift.

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INTRODUCTION

The equal energy hypothesis (EEH), that has been used to establish and implement noise guidelines (e.g., ISO 1999), assumes that the cochlear impact of noise exposure is proportional to the duration of exposure multiplied by the energy intensity of the exposure. The EEH is the basis for the 3-dB exchange rate, that is, equivalent effects for a 3-dB increase or decrease in exposure level with a halving or doubling of the exposure duration, respectively. The EEH thus implies that hearing loss is independent of how the acoustic energy is distributed in time (i.e., the temporal characteristics of the noise). This approach is generally considered appropriate for continuous or steady state noise but not for complex noise (Ahroon et al. 1993; Zhao et al. 2010). Steady state noise exposure has a normal or Gaussian amplitude distribution. Therefore, the temporal characteristics of steady state noise do not change over time. A complex noise is a non-Gaussian noise consisting of a Gaussian 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. Jobs involving maintenance work, metalwork, and power tools, such as impact wrenches and nail guns, provide examples of complex noise environments. Industrial workers are often exposed to complex noise environments. Noises of the same or similar energies and spectra can have very different effects on hearing as a result of their different temporal structures.

The ISO 1999 (2013) document is currently the most widely-accepted model of noise-induced hearing loss (NIHL). Multiple studies have suggested that the model may underestimate NIHL (e.g., Thiery & Meyer-Bisch 1988; Zhao et al. 2010; Xie et al. 2016; Lempert, 2019). Controversy exists over the accuracy of the ISO model in representing the epidemiological data referenced in ISO 1999 and its ability to accurately predict NIHL in individuals. The variability in the ISO 1999 curves relating noise-induced permanent threshold shift (NIPTS) to years of exposure at various exposure levels can exceed 70 dB (Lutman & Davis 1996; Mills et al. 1996). The fundamental problem with the ISO 1999 is its reliance on an acoustic energy metric to quantify an exposure. An acoustic energy metric does not adequately account for the effects of temporal variables known to be important in affecting hearing loss induced by complex noise (Canlon et al. 1988; Clark 1991; Ward, 1991; Hamernik et al. 2003). The National Institute for Occupational

Safety and Health (NIOSH) criteria document (1998) emphasized the paucity of data on the effects of temporal variables especially when the noise environments contain high-level transients, either impacts or noise bursts, that is, when it is impulsive or complex (non-Gaussian). Well-controlled animal studies (Hamernik & Qiu 2001; Hamernik et al. 2003; Qiu et al. 2013) have shown that to fully evaluate the effect of complex noise on hearing, the temporal distribution of noise waveforms need to be considered.

High-level complex noise exposures are very common in industrial environments and pose a hazard to hearing for large numbers of exposed workers. Over the past several decades, a number of published articles have shown, in animal models, that exposure to non-Gaussian complex noise produces more hearing loss and sensory cell loss than does an equivalent energy exposure to continuous Gaussian noise (e.g., Dunn et al. 1991; Lei et al. 1994; Lataye & Campo 1996; Hamernik & Qiu 2001; Hamernik et al. 2003; Qiu et al. 2006, 2007, and 2013). These results along with similar findings from limited human demographic data (Sulkowski et al. 1983; Taylor et al. 1984; Thiery & Meyer-Bisch 1988, Zhao et al. 2010; Davis et al. 2012; Xie et al. 2016) challenge the use of the EEH that forms the basis of current criteria for human exposure to noise (e.g., ISO 1999). Lempert (2019) rechecked the prediction formula for hearing threshold levels (HTLs) in the versions of ISO 1999:1990 and ISO 1999:2013 by using the data from Burns and Robinson (1970) and Passchier-Vermeer (1977), which provided the basis of ISO 1999:1990. He found that the mathematical formulation in ISO 1999 did not closely predict the observed distribution of HTLs in these two databases. As a result, lower predictions of the risk of noise-induced hearing impairment were found using ISO 1999:2013.

Because the temporal distribution of noise waveforms is not taken into account when using an acoustic energy metric and because many diverse noise environments could be characterized by the same energy and spectrum, it seems reasonable that a metric that would incorporate and reflect the temporal structure of an exposure might be a useful adjunct to the equivalent sound pressure level (L_{eq}) metric. One such metric is the kurtosis of a sample distribution. The statistical metric kurtosis (β), an index of the extent to which the distribution of a variable deviates from the Gaussian, is defined as the ratio of the fourth-order central moment to the squared second-order central moment of a distribution. It's worth noting that Gaussian noise has a kurtosis of $\beta = 3$. A non-Gaussian noise, as defined above implies $\beta > 3$, can be effectively modeled as a combination of Gaussian noise with a variety of high-level transients superimposed. The transients may be impacts or noise bursts of varying peak intensities, inter-transient intervals, and durations. The distribution of the high-level transient peaks, inter-transient intervals, and transient durations are all known to affect the outcome of exposure. One way of quantifying the complex temporal structure of a non-Gaussian noise is to measure the peak, interval, and duration histograms of the transients in the noise signal. The kurtosis value is sensitive to, and to a large extent is determined by these three primary variables. It also has the advantage that the temporal structure of a complex noise can be incorporated into a single easily computed number, that is, kurtosis (Erdreich 1986). Thus, kurtosis is a description of the "impulsiveness" of noise exposure. For a given length of noise exposure, the higher the kurtosis of the noise, the higher the impulsiveness of the noise.

Results from animal experiments (Hamernik et al. 2003; Qiu et al. 2006, 2007, and 2013) have shown that: (a) kurtosis is an important variable in assessing the extent of hearing loss from complex noise; and (b) the kurtosis, for a fixed energy level, had a direct impact on the extent of hearing and sensory cell loss from a variety of complex noise exposures, that is, NIHL increased as the kurtosis increased. For human participants, two questions need to be answered: (1) How accurately does the ISO 1999 standard, developed from the results of steady state (Gaussian) noise exposures, and quantified by A-weighted energy alone, predict NIHL from non-Gaussian complex noise environments? (2) Does the kurtosis value of the noise exposure help predict the extent of hearing trauma as it does in animal models (e.g., Hamernik et al. 2003; Qiu et al., 2013)?

In this study, a large human database (N = 2,333), consisting of full work-shift noise recordings and prework-shift hearing levels was acquired from workers in multiple industries in China. The noise environments in these industries had a variety of noise levels and kurtosis values that allowed for a comprehensive evaluation of the applicability of the ISO 1999:2013 prediction model and the role of kurtosis in assessing NIHL.

MATERIALS AND METHODS

Study Design

Audiometric and shift-long noise exposure data were analyzed from a group of 2,333 workers from 34 industries in China. The entire cohort was exclusively divided based on four noise exposure levels ($85 \le L_{Aeq.8h} < 88$, $88 \le L_{Aeq.8h} < 91$, $91 \le L_{Aeq.8h} < 94$, and $94 \le L_{Aeq.8h} \le 100$ dBA), two exposure durations ($D \le 10$ years and $D > 10$ years), and four kurtosis categories (Gaussian, low-, medium-, and high-kurtosis).

A cross-sectional approach was used in this study. The main study elements were (1) workplace selection based upon noise and employment characteristics, (2) recruitment of participants, (3) questionnaire survey, (4) collection of full-shift noise waveforms, (5) calculation of noise metrics, (6) audiometric evaluation, (7) evaluation of ISO 1999 NIPTS predictions, and (8) statistical analysis design. The details of each element are addressed below.

Workplace Selection

Workplace selection for this study was based upon criteria designed to assure necessary Gaussian and non-Gaussian noise exposure and a sufficient participant pool. Each workplace included in the study had (1) a workforce that was stable over last 35 years, (2) work processes and machinery that were stable for at least 35 years, and (3) sufficiently high Gaussian and non-Gaussian noise exposure work areas. Before the data collection, a hygienist interviewed the administrators of the investigated factories to verify that the working environment remained constant. The members of the research team conducted field observations to preliminarily evaluate the noise levels and noise types of in the selected workplaces. A total of 98 workplaces from 34 factories were investigated.

Recruitment of Participants

Industrial workers were recruited from 34 factories in the Zhejiang province of China between 2010 and 2018. Participants (N = 3,244) were introduced to the study purpose and design by occupational physicians and invited to participate.

Those who agreed to participate were asked to sign an informed consent form. The Zhejiang Provincial Center for Disease Control and Prevention (ZJCDC) institutional committee for the protection of human subjects approved the study protocol (approval reference number: ZJCDC-T-043-R).

For inclusion in the study, participants had to satisfy the following four criteria: (1) consistently worked in the same job category and at the same worksite (noise exposure area) for the period from the beginning of a worker's career to the date of the investigation; (2) a minimum of at least 1 year of employment in their current position; (3) no history of genetic or drug-related hearing loss, head wounds, or ear diseases; and (4) no history of military service, firearm use, or setting off firecrackers. As a result, a total of 2,333 were included from the original pool of 3,244 participants.

Most participants still did not use a hearing protection device (HPD) despite the implementation of hearing conservation programs on a wide scale in China starting in 2012. The use of HPDs, usually earplugs, both on and off the job was assessed through field observations by the researchers and in the questionnaire and reported to be low and infrequent. At high noise exposure levels, that is, ~95 dBA and above, the use of HPDs was observed to be sporadic. The inclusion of these participants would, to some extent, have an effect on the relation between noise level and NIPTS. We expected this effect to occur primarily in the participants exposed to noise above 95 dBA. For those participants who have never used HPDs, the members of the research team recommended the use of appropriate HPDs after data collection. During this study, workers in the investigated factories received training on how to properly use HPDs; in a few cases, training included fit testing using the 3M™ E-A-Rfit Dual-Ear Validation System.

Questionnaire Survey

An occupational hygienist from ZJCDC administered a questionnaire to each participant to collect the following information: general demographic information (age, sex, etc.); occupational history (factory, worksite, job description, length of employment, duration of daily noise exposure, and history of using hearing protection); and overall health status (including history of ear disease and ototoxic drug exposure). An occupational physician entered all information into a database.

Noise Data Collection

Shift-long noise recordings were obtained for each noise-exposed participant at the 34 factories using an ASV5910-R digital recorder (Hangzhou Aihua Instruments Co., Hangzhou, China). The ASV5910-R digital recorder is a specialized sound recording device that can be used for precision measurements and analysis of personal noise exposure. The instrument uses a ¼-inch prepolarized condenser microphone characterized by good stability, high upper measurement limit, and wide frequency response (20 Hz–20 kHz). The sensitivity level of the microphone is 2.24 mV/Pa, and the measurement range is 40–141 dBA. One full-shift recording of each participant's noise exposure was captured by the ASV5910-R at 32-bit resolution with a 48-kHz sampling rate and saved in a raw audio format (WAV file). The noise record was saved on a 32 GB micro SD card and transferred to a portable hard disk for subsequent analysis. Before recording, the hygienist confirmed with the manager of the workplace, and each participant that this was the noise they were typically exposed to on an average working day. The members of the research team monitored the noise collection of individual participants in the workplace.

Calculation of Noise Metrics

Two noise metrics were used in this study: (1) A-weighted noise exposure level normalized to a nominal 8-hour working day ($L_{Aeq,8h}$) and (2) kurtosis of noise exposure (β). A program using MATLAB (The MathWorks, R2017) software was developed for analyzing the full-shift noise waveforms that were collected on each participant. The program was designed to extract the $L_{Aeq,8h,}$ and kurtosis, that is,

(1) $L_{Aeq,8h}$ level, in decibels, is given by the formula (ISO 1999, 2013):

$$L_{Aeq,8h} = L_{Aeq,T_e} + 10\log(T_e / T_0) \quad (1)$$

where $L_{Aeq,Te}$ is the A-weighted equivalent continuous sound pressure level for T_e; T_e is the effective duration of the working day in hours, and T_0 is the reference duration (T_0 = 8 hr).

(2) The kurtosis of the recorded noise signal was computed over consecutive 40-second time windows without overlap over the shift-long noise record using a sampling rate of 48 kHz. For a sample of n values, the kurtosis is calculated as:

$$\beta = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^4 / (\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2)^2 \quad (2)$$

where x_i is the ith value and $\bar{x}$ is the sample mean. Because the kurtosis value is dependent on the length of the window over which the calculation is made, and its calculation is limited by the computer's processing capabilities, a compromise was made to use a 40-second time window which, based on previous animal data (Hamernik et al. 2003), was found to be sufficient to establish an acceptable measure of the kurtosis metric. The mean of the measured kurtosis values was calculated and used as the kurtosis metric.

Audiometric Evaluation

Each participant underwent a general physical and otologic examination. Otoscopy was carried out initially to ensure participants had no external ear abnormalities. Air conduction pure tone HTLs were tested at 0.5, 1, 2, 3, 4, 6, and 8 kHz in each ear by a certified audiologist. The tests were conducted manually. Each participant's hearing data was recorded on a separate audiogram form and all the data were entered into a computer after the daily test was completed. 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 S3.1-1999 specifications from 125 to 8000 Hz (ANSI, 2003). Audiograms were measured at least 16 hours after the participants' last occupational noise exposure.

Evaluation of ISO 1999 median NIPTS predictions

A database composed of the participant's shift-long temporal noise waveform and the associated audiometric results was developed and compared to the ISO 1999 predictions for median

TABLE 1. A breakdown of the average noise exposure level, duration of exposure, kurtosis, age, and sex, corresponding to the number of subjects exposed by categories of industry

				Participants					
Industry Category	Main Productions	Number of Factories	Typical Noise Sources	Male (n)	Female (n)	Age (year)*	Duration (year)*	$L_{Aeq,8h}$ (dBA)*	Mean Kurtosis*
Textile	Spandex, woven bag, and cotton textile	4	Spinning, weaving	127	174	33.0 ± 8.4 (17–58)	8.2 ± 6.3 (1–35)	95.3 ± 3.6 (85–100)	9.0 ± 11.8 (3–139)
Paper	Paper	2	Pulping	55	30	46.8 ± 10.2 (20–65)	11.6 ± 8.4 (1–35)	89.8 ± 3.0 (85–97)	9.9. ± 8.1 (3–52)
Furniture	Furniture	6	Gunning, nailing	297	37	34.7 ± 9.7 (18–63)	5.0 ± 4.7 (1–31)	90.1 ± 3.0 (85–99)	188.2 ± 161.4 (13–925)
Vehicle	Car parts, brake pad, wheel, suspension spring, and vehicle engine	7	Cold heading, machining, stamping	770	200	35.3 ± 7.5 (19–59)	11.2 ± 8.0 (1–35)	90.2 ± 3.4 (85–100)	26.5 ± 36.4 (3–647)
Hardware	Hardware tools and components	2	Drilling, blast sand, forging, polishing	65	39	41.0 ± 8.7 (19–59)	13.1 ± 8.8 (1–35)	93.7 ± 4.1 (85–100)	12.9 ± 12.1 (3–52)
Electrical equipment	Electrical equipment, washing machine	2	Polishing, Stamping, assembling, sanding	50	9	26.8 ± 4.7 (19–39)	3.9 ± 4.3 (1–19)	90.0 ± 3.2 (85–100)	18.8 ± 12.0 (4–77)
Pipe	Oil pipeline	2	Cutting, mending, polishing	49	3	31.2 ± 9.4 (20–55)	5.6 ± 6.4 (1–35)	90.5 ± 3.0 (85–98)	34.7 ± 16.8 (8–76)
Machinery	Mechanical products, tool and mold, hydroelectric equipment	6	Metal processing, cutting, welding, casting, grinding	165	114	40.1 ± 9.8 (20–65)	8.6 ± 6.6 (1–35)	90.8 ± 4.0 (85–100)	34.0 ± 32.8 (4–241)
Steel	Iron and steel products, steel frame structure	3	Steel rolling, and finishing, welding, drilling, assembling	148	0	38.9 ± 7.1 (20–53)	13.3 ± 8.2 (1–33)	93.8 ± 3.5 (86–100)	41.2 ± 55.3 (5–316)
Summary		34		1,727	606	36.1 ± 9.1 (17–65)	9.5 ± 7.7 (1–35)	91.3 ± 3.9 (85–100)	48.0 ± 89.4 (3–925)

**, plus/minus 1 standard deviation (minimum to maximum).*

NIPTS. The ISO 1999 median NIPTS prediction for each participant was determined using the equations described in the ISO 1999 document as follows:

$$NIPTS = \begin{cases} \left[u + v\log\left(\frac{t}{t_0}\right)\right]\left(L_{Aeq,8h} - L_0\right)^2, \ 10 \le t \le 40 \\ \frac{log(t+1)}{log(11)}\left[u + v\log\left(\frac{10}{t_0}\right)\right]\left(L_{Aeq,8h} - L_0\right)^2, \ t < 10 \end{cases} \quad (3)$$

where $L_{Aeq,8h}$ is the noise exposure level normalized to a nominal 8 hr working day; t is noise exposure duration in years, $t_0 = 1$; L_0 is the reference sound pressure level in Table 1 of ISO 1999 (2013); u and v are coefficients given as a function of audiometric test frequency in Table I of ISO 1999 (2013).

The analysis focused on the frequency range of 2–6 kHz because noise-induced hearing loss occurs predominantly in this range. The NIPTS predictions for each participant at test frequencies (2, 3, 4, and 6 kHz) were obtained by subtracting normal median HTLs by age- and sex-matched populations adapted from the ISO 1999 (2013) Table B.3 (derived from an audiometric survey of the U.S. population in 1960 to 2006). The thresholds of the better ear were determined for all participants across the test frequencies. The better ear was used because this was the criteria for Table B.3 of the ISO 1999 (Hoffman et al., 2010). Because the participants were exposed to only one occupational high-level noise throughout their working life and since their working environments were never changed, the observed hearing loss estimates were likely attributable to the measured industrial noise exposures.

The above approach allowed us to compare the ISO 1999 NIPTS predictions for each exposure condition to the actual NIPTS incurred by the participant under the same exposure condition. Three noise-related metrics (i.e., noise level, duration, and kurtosis) were used to evaluate noise-induced hearing loss in this study. To evaluate the effect of noise level on NIPTS, participants were classified into the following four exposure groups:

(1) L_1: $85 \le L_{Aeq.8h} < 88$ dBA;
(2) L_2: $88 \le L_{Aeq.8h} < 91$dBA;
(3) L_3: $91 \le L_{Aeq.8h} < 94$ dBA;
(4) L_4: $94 \le L_{Aeq.8h} \le 100$ dBA.

Because NIHL develops most rapidly during the first 10 years of noise exposure and then slows with additional noise exposure

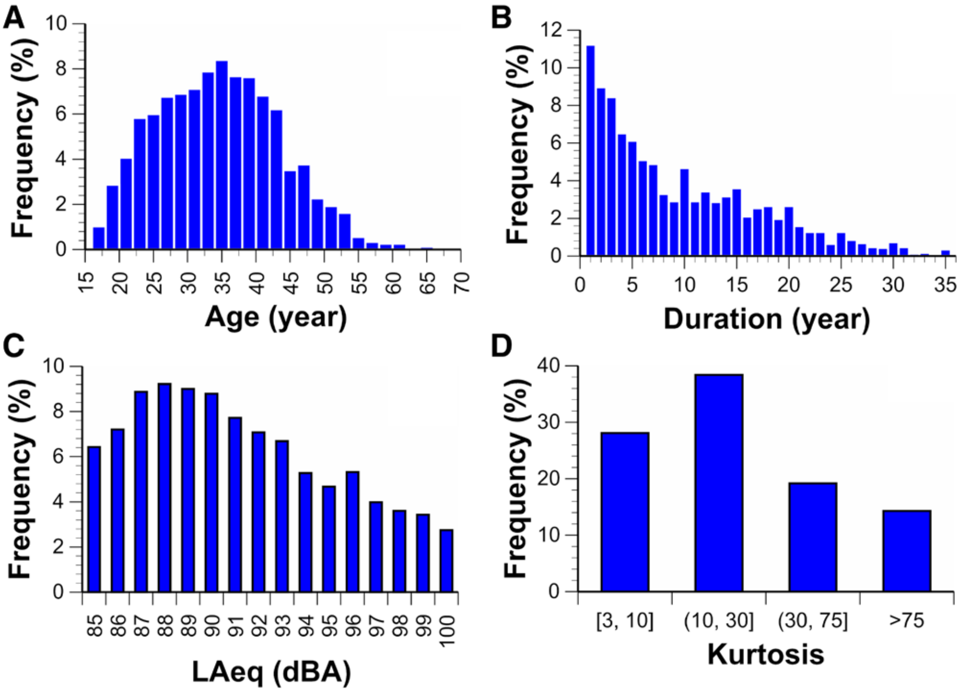

Fig. 1. Distributions of (A) age; (B) exposure duration; (C) A-weighted equivalent sound pressure levels ($L_{Aeq.8h}$); and (*D*) kurtosis value of the 2,333 noise-exposed workers.

(ISO 1999, 2013; NIOSH 1998; Dobie 2001; Davis et al. 2012) groups were further divided into two subgroups based on the duration (*D*) of noise exposure:

(i) D_1: $1 \leq D \leq 10$ years (denoted by $D \leq 10$);

(ii) D_2: $10 < D \leq 35$ years (denoted by $D > 10$).

To evaluate the effect of kurtosis on NIPTS, participants were partitioned into one of four groups based on the kurtosis value of noise exposure. The selection of the partitioning bins for the kurtosis metric was based on previous animal experiments where the noise-induced sensory cell loss was documented by noises with kurtosis β = 3, 25, 50, or 100 at 97 dB SPL. The results showed that cochlear sensory cell loss increased with increasing β(t) (Qiu et al. 2013). Thus, the grouping strategy of this study was as follows:

(a) K_1: Gaussian/quasi-Gaussian group [mean $\beta(t) \leq 10$];
(b) K_2: Low kurtosis group [$10 <$ mean $\beta(t) \leq 30$];
(c) K_3: Medium kurtosis group [$30 <$ mean $\beta(t) \leq 75$];
(d) K_4: High kurtosis group [mean $\beta(t) > 75$].

A quasi-Gaussian noise was defined as noise whose amplitude distribution was close to the Gaussian distribution. In this study, noise with kurtosis range of 2.8 to 3.9 was considered as Gaussian noise, and noise with kurtosis range of 4 to 10 was considered as quasi-Gaussian noise.

Statistical Analysis

Noise exposure level ($L_{Aeq.8h}$), duration of exposure, kurtosis, age, and sex were summarized as count, mean, and standard deviation or range (minimum to maximum). The actual measured NIPTS and the difference between the actual NIPTS and the ISO 1999 predicted NIPTS were analyzed using a mixed model where the NIPTS or the NIPTS difference served as the dependent variable, while noise level ($L_{Aeq.8h}$), exposure duration, kurtosis as well as their interaction served as independent variables. The group means for level, duration, and kurtosis, and their 95% confidence interval (CI) were calculated. The estimated marginal means and standard errors of NIPTS difference and the actual measured NIPTS are plotted in Figures 2 and 3. A significance level of $p < 0.05$ was applied to the overall test for all factors and their interaction. Pairwise comparisons were processed among noise level, duration, and kurtosis groups. For all pairwise comparisons, Bonferroni adjustment was applied in claiming significance. The analyses were performed using IBM SPSS Statistics (version 22).

RESULTS

Data were collected on 2,333 workers exposed to a variety of industrial noises. Table 1 provides a breakdown by the factory of the average noise exposure level, duration of exposure, kurtosis, age, and sex, corresponding to the number of participants exposed. The distributions of participant age, exposure duration, and noise exposure level (L_{Aeq}) in the 2,333 noise-exposed participants are presented in Figure 1. As can be seen in Figure 1A, most of the participants were between 22 and 48 years old (88.6%). The median age of the group was 36 years, the mean was 36.1 years. The exposure duration for the 2,333 participants ranged from 1 to 35 years as shown in Figure 1B. The median duration was 7 years, the mean was 9.5 years, and 42.6% had more than 10 years. Figure 1C shows that about 24% of the participants were exposed to levels between 85–87 dBA; 28% of participants to levels between 88 and 90 dBA; 23% participants to levels between 91 and 93 dBA; and 25% of participants to levels between 94 and 100 dBA. The median level was 90.8 dBA; the mean was 91.3 dBA. Figure 1D shows that about 28% of participants were exposed to a Gaussian/quasi-Gaussian

TABLE 2. Estimated marginal means and standard errors of NIPTS difference between the actual measured NIPTS and the ISO 1999 predicted NIPTS for level, duration, kurtosis, and level by duration groups

Effect	Group	Estimated Mean	Standard Error	95% CI
L_{Aeq}*	L_1	12.6	0.6	11.5 to 13.7
	L_2	11.9	0.5	10. 9 to 12.8
	L_3	9.8	0.5	8. 8 to 10.8
	L_4	4.4	0.5	3.4 to 5.5
Duration†	D_1	11.4	0.3	10.8 to 12.0
	D_2	8.0	0.4	7.1 to 8.8
Duration × L_{Aeq}	$D_1 \times L_1$	13.1	0.5	12.0 to 14.1
	$D_1 \times L_2$	13.7	0.5	12.8 to 14.7
	$D_1 \times L_3$	10.7	0.6	9.6 to 11.8
	$D_1 \times L_4$	8.0	0.7	6.7 to 9.3
	$D_2 \times L_1$	12.1	1.1	9.9 to 14.3
	$D_2 \times L_2$	10.0	0.9	8.2 to 11.8
	$D_2 \times L_3$	8.8	0.9	7.1 to 10.6
	$D_2 \times L_4$	0.9	0.9	−0.9 to 2.8
Kurtosis‡	K_1	7.5	0.4	6.6 to 8.3
	K_2	8.7	0.4	8.0 to 9.4
	K_3	8.9	0.5	7.8 to 9.8
	K_4	13.6	0.7	12.2 to 15.1

CI, confidence interval; NIPTS, noise-induced permanent threshold shift.
p values for difference between level group pair are as follows: 1.0 for L_1–L_2 pair; 0.001 for L_1–L_3 pair; <0.001** for L_1–L_4 pair; 0.017** for L_2–L_3 pair; <0.001** for L_2–L_4 pair; <0.001** for L_3–L_4 pair.*
*†p value for difference between D_1 and D_2 is <0.001**.*
*‡p values for difference between kurtosis group pair are as follows: 0.162 for K_1–K_2 pair; 0.259 for K_1–K_3 pair; <0.001** for K_1–K_4 pair; 1.0 for K_2–K_3 pair; <0.001** for K_2–K_4 pair; <0.001** for K_3–K_4 pair.*
***Statistically significant. Bonferroni adjustment was applied for multiple comparisons.*

noise; 38% to low-kurtosis noise; 19% to medium-kurtosis noise; and 15% to high-kurtosis noise. The median kurtosis value was 18.2, the mean value was 48.

Evaluation of the ISO 1999 NIPTS predictions

Overall Difference Between the ISO 1999 Predicted NIPTS and the Actual Measured NIPTS • To evaluate the difference between the ISO 1999 predicted NIPTS and the actual measured NIPTS, the average of the actual measured NIPTS over 2, 3, 4, and 6 kHz for each participant was used to compare with the ISO 1999 predicted NIPTS. The overall NIPTS difference was 9.2 dB (95% CI: 8.8–9.7) with $p < 0.001$ where the ISO 1999 predicted NIPTS was 8.0 dB and the measured NIPTS was 17.2 dB. Overall, the ISO 1999 prediction model significantly underestimated the NIPTS by 9.2 dB on average.

Evaluation of the ISO 1999 NIPTS Prediction • The mixed model analysis showed that there was a significant kurtosis effect ($F = 17.1$, $p < 0.001$), duration effect ($F = 40.9$, $p < 0.001$), level effect ($F = 44.8$, $p < 0.001$), and duration by level interaction effect ($F = 5.9$, $p = 0.001$) on the NIPTS difference. The estimated marginal mean for each group is summarized in Table 2. Although there is a significant duration by level interaction, the increasing trend of the NIPTS difference with the noise level is consistent between the two duration groups making the evaluation of marginal mean of duration or level meaningful.

The effect of exposure duration on NIPTS underestimation • The ISO 1999 prediction model underestimated NIPTS by 11.4 dB in participants having an exposure duration $D \leq 10$ years, while the NIPTS underestimation was 8.0 dB in participants with duration $D > 10$ years. The degree of underestimation in NIPTS between two duration groups was significantly different ($p < 0.001$).

The effect of noise level on NIPTS underestimation • The ISO 1999 model underestimated NIPTS by 12.6, 11.9, 9.8, and 4.4 dB in participants exposed to noise with levels of $85 \leq L_{Aeq.8h} < 88$ dBA (group L_1), $88 \leq L_{Aeq.8h} < 91$dBA (group L_2), $91 \leq L_{Aeq.8h} < 94$ dBA (group L_3), and $94 \leq L_{Aeq.8h} \leq 100$ dBA (group L_4), respectively. The extent by which the ISO prediction model underestimated the NIPTS decreased with the increase of noise level. The degree of NIPTS underestimation was significantly smaller in the L_4 level group than in the other three level groups ($p < 0.001$ for all three comparisons). The degree of NIPTS underestimation in the L_3 level group was significantly less than in the L_1 and L_2 groups ($p = 0.001$ and 0.017, respectively). There was no significant difference between L_1 and L_2 level groups in NIPTS underestimation.

Interaction effect of duration by level on NIPTS underestimation • The results showed that there was a significant interaction effect in the noise level by exposure duration on NIPTS underestimation by the ISO 1999 prediction model. From Table 2, it can be seen that different combinations of noise level and exposure duration produced different amounts of NIPTS underestimation. For exposure duration $D \leq 10$ years, the ISO 1999 prediction model underestimated NIPTS by 8.0 to 13.7 dB on average across different noise levels. For exposure duration $D > 10$ years, the ISO 1999 model underestimated NIPTS by 0.9 to 12.1 dB on average across different noise levels. For a fixed duration, the degree of NIPTS underestimation decreased as the noise level increased.

The effect of kurtosis on NIPTS underestimation • The ISO 1999 model underestimated NIPTS by 7.5 dB for the Gaussian/quasi-Gaussian kurtosis group (K_1); by 8.7 dB for the low kurtosis group (K_2); by 8.9 dB for the medium kurtosis group (K_3); and by 13.6 dB for the high kurtosis group (K_4). The extent of NIPTS underestimation increased with the increase of kurtosis value. The underestimated NIPTS by the ISO 1999 model for the K_4 kurtosis group was significantly larger than that of the other three kurtosis groups (p<0.001 for all 3 comparisons).

Effects of Noise Level and Kurtosis on NIPTS Underestimation for Two Exposure Durations • The effects of noise level and kurtosis on NIPTS differences were analyzed for the D_1 duration group (N = 1,340) and the D_2 group (N = 993). The mixed-model analysis showed that: (1) there was a significant kurtosis effect ($F = 19.7$, $p < 0.001$) and level effect ($F = 19.6$, $p < 0.001$) on the NIPTS difference in D_1 group; (2) there was a significant kurtosis effect ($F = 5.2$, $p = 0.001$) and level effect ($F = 25.6$, $p < 0.001$) on the NIPTS difference in D_2 group. The estimated marginal means for the D_1 and D_2 groups are summarized in Tables 3. The effects of noise level and kurtosis on underestimated NIPTS by ISO 1999 for these two exposure durations are shown in Figure 2. For the $D \leq 10$-year group (Figure 2A), the ISO 1999 model underestimated NIPTS by 6.1 to 11.5 dB in participants exposed to Gaussian (K_1) noise and 7.6 to 17.1 dB in participants exposed to non-Gaussian (K_2, K_3, and K_4) noise at all four noise levels (L_1 to L_4). For a fixed noise level, the amount by which the ISO 1999 model

TABLE 3. Estimated marginal means and standard errors of NIPTS difference for level and kurtosis groups at duration *D* ≤ 10 years and *D* > 10 years

Duration	Effect	Group	Estimated Mean	Standard Error	95% CI
$D \le 10$ years	L_{Aeq}*	L_1	13.1	0.5	12.0 to 14.1
		L_2	13.7	0.5	12.8 to 14.7
		L_3	10.7	0.6	9.6 to 11.8
		L_4	8.0	0.7	6.7 to 9.3
	Kurtosis†	K_1	9.0	0.5	8.0 to 10.0
		K_2	10.9	0.4	10.1 to 11.8
		K_3	11.2	0.7	9.8 to 12.5
		K_4	14.8	0.6	13.7 to 15.9
$D > 10$ years	L_{Aeq}‡	L_1	12.1	1.1	9.9 to 14.3
		L_2	10.0	0.9	8.2 to 11.8
		L_3	8.8	0.9	7.1 to 10.6
		L_4	0.9	0.9	−0.9 to 2.8
	Kurtosis§	K_1	6.0	0.7	4.5 to 7.4
		K_2	6.5	0.6	5.4 to 7.7
		K_3	6.9	0.7	5.5 to 8.4
		K_4	12.4	1.5	9.5 to 15.4

CI, confidence interval; NIPTS, noise-induced permanent threshold shift.
For duration, D ≤ 10 years:
The p values for difference between level group pair are as follows: 1.0 for L_1–L_2 pair; 0.013 for L_1–L_3 pair; <0.001** for L_1–L_4 pair; <0.001** for L_2–L_3 pair; <0.001** for L_2–L_4 pair; 0.009** for L_3–L_4 pair.*
*†The p values for difference between kurtosis group pair are as follows: 0.027** for K_1–K_2 pair; 0.012** for K_1–K_3 pair; <0.001** for K_1–K_4 pair; 1.0 for K_2–K_3 pair; <0.001** for K_2–K_4 pair; <0.001** for K_3–K_4 pair.*
For Duration D > 10 years:
*‡The p values for difference between level group pair are as follows: 0.889 for L_1–L_2 pair; 0.128 for L_1–L_3 pair; <0.001** for L_1–L_4 pair; 1.0 for L_2–L_3 pair; <0.001** for L_2–L_4 pair; <0.001** for L_3–L_4 pair.*
*§The p values for difference between kurtosis group pair are as follows: 1.0 for K_1–K_2 pair; 1.0 for K_1–K_3 pair; 0.001** for K_1–K_4 pair; 1.0 for K_2–K_3 pair; 0.001** for K_2–K_4 pair; 0.007** for K_3–K_4 pair.*
***Statistically significant. Bonferroni adjustment was applied for multiple comparisons.*

TABLE 4. Estimated marginal means and standard errors of the actual measured NIPTS for level, duration, kurtosis groups

Effect	Group	Estimated Mean	Standard Error	95% CI
L_{Aeq}*	L_1	16.9	0.7	15.5 to 18.2
	L_2	18.7	0.6	17.6 to 19.9
	L_3	20.6	0.6	19.4 to 21.7
	L_4	20.8	0.7	19.3 to 22.1
Duration†	D_1	18.0	0.4	17.3 to 18.7
	D_2	20.4	0.5	19.4 to 21.4
Kurtosis‡	K_1	16.6	0.5	15.5 to 17.6
	K_2	18.2	0.4	17.4 to 19.1
	K_3	18.9	0.6	17.7 to 20.0
	K_4	23.1	0.9	21.3 to 24.8

CI, confidence interval; NIPTS, noise-induced permanent threshold shift.
p values for difference between level group pair are as follows: 0.238 for L_1–L_2 pair; <0.001 for L_1–L_3 pair; <0.001** for L_1–L_4 pair; 0.15 for L_2–L_3 pair; 0.195 for L_2–L_4 pair; 1.0 for L_3–L_4 pair.*
*†p value for difference between D_1 and D_2 is <0.001**.*
*‡The p values for difference between kurtosis group pair are as follows: 0.076 for K_1–K_2 pair; 0.024** for K_1–K_3 pair; <0.001** for K_1–K_4 pair; 0.832 for K_2–K_3 pair; <0.001** for K_2–K_4 pair; 0.001** for K_3–K_4 pair.*
***Statistically significant. Bonferroni adjustment was applied for multiple comparisons.*

underestimated NIPTS increased as the kurtosis value increased in the order K_1, K_2, K_3, and K_4. Except for the K_2-K_3 group pair, the underestimated NIPTS by the ISO 1999 model for all other kurtosis group pairs was significantly different ($p < 0.001$ to 0.027, Table 3). Also evident from these data is that for a fixed kurtosis value, the extent of NIPTS underestimation deceased as the noise level increased. The degree of NIPTS underestimation at the L_4 level was significantly less than that of the other three levels ($p < 0.001$ to 0.009, Table 3). The amount of NIPTS underestimation at the L_3 level was also significantly less than that of the L_2 and L_1 levels ($p < 0.001$ and $p = 0.013$, Table 3).

For the $D > 10$-year group (Figure 2B), the extent of NIPTS difference continued to increase as the kurtosis value increased. However, only the NIPTS difference of the K_4 kurtosis group was significantly larger than that of the other three kurtosis groups ($p = 0.001$ to 0.007, Table 3). Meanwhile, the degree of NIPTS differences continued to decrease with the increase in noise level, and only the L_4 level group had significantly lower NIPTS differences than the other three level groups ($p < 0.001$ for all three comparisons, Table 3).

Evaluation of the Effects of Level, Duration, and Kurtosis on the Actual Measured NIPTS

Effects of Noise Level, Exposure Duration, and Kurtosis on the Actual Measured NIPTS • The average of the actual measured NIPTS over 2, 3, 4, and 6 kHz for each participant was used in the study. The mixed model analysis showed that there was a significant duration effect ($F = 14.0$, $p < 0.001$), level effect ($F = 7.5$, $p < 0.001$), and kurtosis effect ($F = 13.8$, $p < 0.001$) on the actual measured NIPTS. The estimated marginal mean for each group is summarized in Table 4.

The effect of exposure duration on the actual measured NIPTS • The actual measured NIPTS was 18.0 dB in participants having an exposure duration $D \le 10$ years, while the measured NIPTS was 20.4 dB in participants with duration $D > 10$ years. The difference in NIPTS between two duration groups was significantly different ($p < 0.001$).

The effect of noise level on the actual measured NIPTS • The actual measured NIPTS were 16.9, 18.7, 20.6, and 20.8 dB for level groups L_1 to L_4, respectively. The measured NIPTS increased with an increase in noise level. However, only the measured NIPTS in the L_1 level group was significantly less than that in the L_3 and L_4 level groups ($p < 0.001$ for both comparisons).

The effect of kurtosis on NIPTS underestimation • The actual measured NIPTS was 16.6 dB for the Gaussian kurtosis group (K_1); 18.2 dB for the low kurtosis group (K_2); 18.9 dB for the medium kurtosis group (K_3); and 23.1 dB for the high kurtosis group (K_4). The NIPTS increased with the increase of kurtosis value in the order K_1, K_2, K_3, and K_4. Except for the K_1–K_2 and K_2–K_3 group pairs, the measured NIPTS for all other kurtosis group pairs was significantly different ($p < 0.001$ to 0.024, Table 4).

Effects of Noise Level and Kurtosis on the Actual Measured NIPTS for Two Exposure Durations • The effects of noise level and kurtosis on the actual measured NIPTS were analyzed for the D_1 and D_2 duration groups. The mixed model analysis showed that: (1) there was a significant kurtosis effect ($F = 17.3$, $p < 0.001$) and level effect ($F = 3.9$, $p = 0.009$) on measured NIPTS in the D_1 group; (2) there was a significant kurtosis effect ($F = 3.7$, $p = 0.012$) and duration effect ($F = 4.9$, $p = 0.002$) on measured NIPTS in the D_2 group. The estimated marginal means for the D_1 and D_2 groups are summarized in Tables 5. The effects of noise level and kurtosis on the actual

TABLE 5. Estimated marginal means and standard errors of the actual measured NIPTS for level and kurtosis groups at duration *D*≤10 years and *D*>10 years

Duration	Effect	Group	Estimated Mean	Standard Error	95% CI
$D \leq 10$ years	L_{Aeq}*	L_1	16.1	0.6	14.9 to 17.4
		L_2	18.6	0.6	17.4 to 19.7
		L_3	18.4	0.7	17.0 to 19.6
		L_4	19.1	0.8	17.6 to 20.6
	Kurtosis†	K_1	15.1	0.6	13.9 to 16.3
		K_2	17.3	0.5	16.2 to 18.3
		K_3	18.1	0.8	16.5 to 19.7
		K_4	21.6	0.7	20.2 to 22.9
$D > 10$ years	L_{Aeq}‡	L_1	17.6	1.3	15.0 to 20.1
		L_2	18.9	1.1	16.7 to 21.0
		L_3	22.9	1.0	20.9 to 24.9
		L_4	22.1	1.1	19.9 to 24.2
	Kurtosis§	K_1	18.1	0.9	16.3 to 19.8
		K_2	19.2	0.7	17.9 to 20.5
		K_3	19.6	0.9	17.8 to 21.3
		K_4	24.5	1.8	21.1 to 28.0

CI, confidence interval; NIPTS, noise-induced permanent threshold shift.
For duration, D ≤ 10 years:
p values for difference between level group pair are as follows: 0.025 for L_1–L_2 pair; 0.028** for L_1–L_3 pair; 0.019** for L_1–L_4 pair; 1.0 for L_2–L_3 pair; 1.0 for L_2–L_4 pair; 1.0 for L_3–L_4 pair.*
*†p values for difference between kurtosis group pair are as follows: 0.04** for K_1–K_2 pair; 0.017** for K_1–K_3 pair; <0.001** for K_1–K_4 pair; 1.0 for K_2–K_3 pair; <0.001** for K_2–K_4 pair; 0.008** for K_3–K_4 pair.*
For duration, D > 10 years:
*‡p values for difference between level group pair are as follows: 0.586 for L_1–L_2 pair; 0.008** for L_1–L_3 pair; 0.047** for L_1–L_4 pair; 0.043** for L_2–L_3 pair; 0.218 for L_2–L_4 pair; 0.875 for L_3–L_4 pair.*
*§ p values for difference between kurtosis group pair are as follows: 1.0 for K_1–K_2 pair; 1.0 for K_1–K_3 pair; 0.003** for K_1–K_4 pair; 1.0 for K_2–K_3 pair; 0.005** for K_2–K_4 pair; 0.025** for K_3–K_4 pair.*
***Statistically significant. Bonferroni adjustment was applied for multiple comparisons.*

measured NIPTS for these two exposure durations are shown in Figure 3. For the $D \leq 10$-year group (Fig. 3A), the effect of kurtosis on the measured NIPTS is obvious, that is, for a fixed noise level, the measured NIPTS increased as the kurtosis increased. Except for the K_2–K_3 group pair, the measured NIPTS for all other kurtosis group pairs was significantly different ($p < 0.001$ to 0.04, Table 5). On the other hand, for a fixed kurtosis value, the measured NIPTS increased as the noise level increased except for the L_3 level group. The measured NIPTS of the L_1 level group was significantly less than that of the other three level groups ($p = 0.019$ to 0.028, Table 5). For the $D>10$-year group (Fig. 3B), the effect of kurtosis on measured NIPTS was no longer as clear as that measured in the first decade of exposure. The differences in NIPTS between Gaussian (K_1), low (K_2), and medium (K_3) kurtosis groups were not significant. However, the measured NIPTS of the high (K_4) kurtosis group was still significantly larger than that of the other three lower kurtosis groups ($p = 0.003$ to 0.025, Table 5).

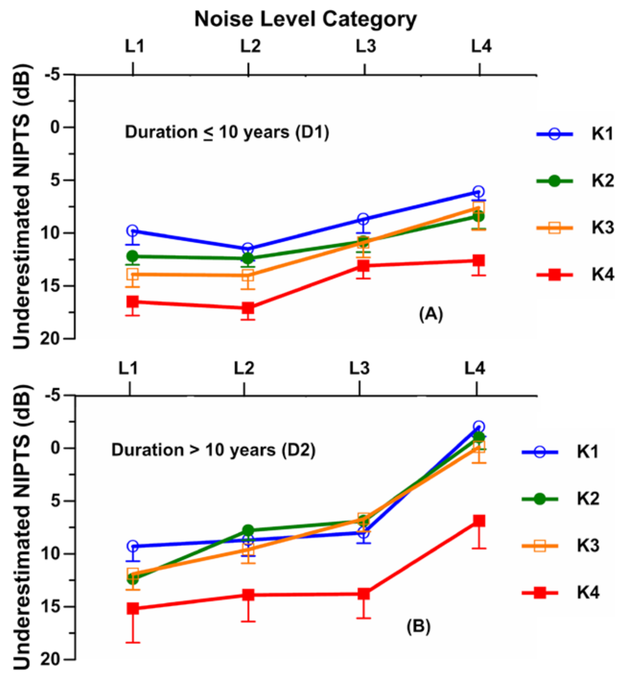

Fig. 2. The estimated marginal means (EMM) of underestimated NIPTS by ISO 1999 model at each kurtosis value across test frequencies for four noise level bins in two different exposure durations. (A) The EMM of NIPTS underestimation at each kurtosis value for our noise level bins in duration $D \leq 10$ years. (B) The EMM of NIPTS underestimation at each kurtosis value for our noise level bins in duration $D > 10$ years. Error bars indicate the standard error of the EMM.

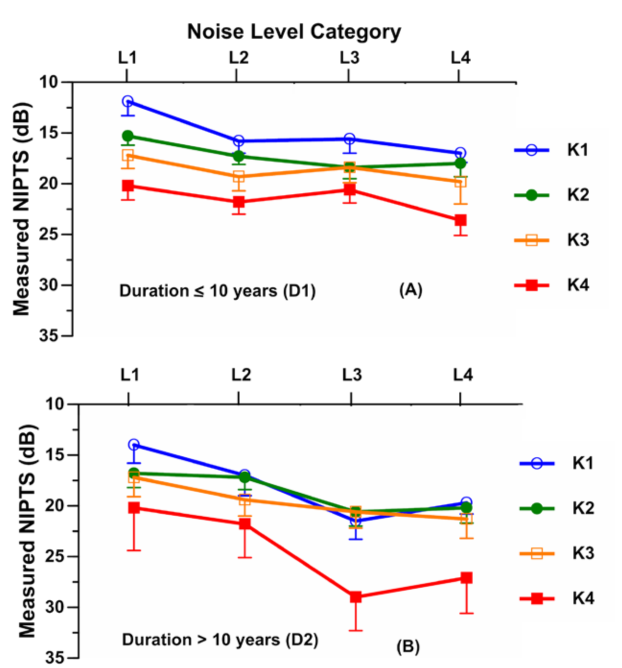

Fig. 3. The estimated marginal means (EMM) of the actual measured NIPTS at each kurtosis value across test frequencies for four noise level bins in two different exposure durations. (A) The EMM of the actual measured NIPTS at each kurtosis value for our noise level bins in duration $D \leq 10$ years. (B) The EMM of the actual measured NIPTS at each kurtosis value for our noise level bins in duration $D > 10$ years. Error bars indicate the standard error of the EMM.

DISCUSSION

The Performance of the ISO 1999 NIPTS Prediction Model

The epidemiological data that formed the ISO 1999 standard was derived from steady or quasi-steady industrial noises and these data were collected over 50 years ago (Thiery &

Meyer-Bisch 1988; Lempert 2019). The results of this study indicate that: (1) ISO 1999 underestimated NIPTS for noise exposure durations less than or equal to 10 years; (2) when the noise level was lower than 94 dBA, the ISO 1999 model underestimated NIPTS for noise exposure durations longer than 10 years. However, when the noise level was higher than 94 dBA and the kurtosis was less than 75, the NIPTS predicted by ISO 1999 was roughly consistent with the actual NIPTS measured; (3) the ISO 1999 model always underestimated noise-induced hearing loss for noise exposures having a kurtosis value over 75; and (4) for the duration $D \leq 10$ years, the amount by which NIPTS was underestimated by the ISO 1999 increased with an increase in kurtosis.

The Role of Kurtosis in Evaluating the NIHL

In the present study, the results from a database collected from 2,333 participants exposed to various industrial noises are in general agreement with animal (chinchilla) model experiments (Lei et al. 1994; Hamernik et al. 2003; Qiu et al. 2006, 2007, 2013) showing that: (1) an acoustic energy metric is necessary but not sufficient to evaluate the hazard of noise to hearing; (2) the temporal distribution of energy of noise (i.e., kurtosis) is an important factor in assessing noise-induced hearing loss; (3) for a fixed energy level, the noise-induced hearing loss increased as the kurtosis of the noise increased; and (4) non-Gaussian complex noises are more hazardous than Gaussian noise exposures of equivalent energy and the hazard is identified by the kurtosis value of the noise. In addition to the above-mentioned conclusions, human data, however, show some peculiarities:

(1) For exposure durations less than or equal to 10 years, the relation between hearing loss (i.e., measured NIPTS) and kurtosis value is clear, that is, for a fixed noise level, noise-induced hearing loss increased as the kurtosis value of the noise increased (as shown in Fig. 3A). In the first decade of exposure to high-level noise, complex noise with a kurtosis $\beta(t) > 10$ was more hazardous than steady state (Gaussian) noise.

(2) It has been reported that NIHL develops most rapidly in the first 10 years and then slows with additional exposure to noise (NIOSH 1998; Dobie 2001). The results in the present study also show a similar pattern for the development of NIHL over time. Moreover, as the exposure duration increased beyond 10 years the difference in NIPTS between the Gaussian, the low, and the medium kurtosis groups [$\beta(t) \leq 75$] tended to fade away (as shown in Fig. 3B). However, the NIPTS in the high kurtosis group [$\beta(t) > 75$] was still significantly larger than that of other groups. This suggests that the presence of impact noise as indicated by these high kurtosis values can cause hearing damage faster and continue over a longer exposure time than predicted by the ISO 1999. The ISO 1999 model most significantly underestimated the degree of hearing loss caused by non-Gaussian noise. The results also suggests that the kurtosis value plays a more important role in assessing NIHL of workers whose exposure time is less than or equal to 10 years, compared with that of workers whose exposure time is more than 10 years.

(3) The measured NIPTS in participants exposed to the lowest level range ($85 \leq L_{Aeq.8h} < 88$ dBA) and for exposure durations $D \leq 10$ years, showed a significant trend to increase as kurtosis value increased (Fig. 3A). This result shows that the effect of kurtosis is particularly important near the permissible exposure level (PEL) of noise, that is, 85 dBA. As shown in Figure 3A, the average measured NIPTS increased from an average of 11.9 dB for the Gaussian level kurtosis to an average of 20.2 dB for the high-level kurtosis at an average rate of 2.8 dB per increment in kurtosis value. The NIPTS difference between Gaussian and high kurtosis was as much as 8.3 dB. Therefore, current exposure limits for non-Gaussian complex noise should be reexamined, especially for non-Gaussian complex noise with high kurtosis value.

(4) For noise levels in the range $94 \leq L_{Aeq.8h} \leq 100$ dBA (L_4) and exposure durations $D > 10$ years, most participants exposed to the high levels of noise wore earplugs sporadically. This may explain why the NIPTS in participants exposed to noises with medium or lower kurtosis values showed little difference in NIPTS compared with ISO 1999 (Fig. 2B). However, despite HPDs, participants exposed to high kurtosis noise still suffered severe hearing loss. This result may suggest that it is necessary to carefully evaluate the protective function of HPDs against impulsive noise, especially when the kurtosis value is larger than 75. When evaluating the hearing protection efficiency of HPDs, in addition to the noise energy attenuation index, it may be necessary to evaluate the attenuation with respect to noise impulsiveness (i.e., kurtosis).

Considering that many industrial noise environments are non-Gaussian and that sound energy metrics (e.g., L_{eq}) are suitable for Gaussian noise, there is a need to implement alternative metrics or a combination of metrics for assessing non-Gaussian noise environments. Results from the present study have shown that the kurtosis measurement is a more precise metric for assessment of hearing loss from complex noise.

In this study, only the data with noise exposure levels between 85 and 100 dBA were used for the NIPTS analysis. The lower limit of applicability of the ISO standard, an $L_{Aeq.8h}$ of 75 dBA, is implicit in the NIPTS calculation method. NIPTS analysis of non-Gaussian noise exposure at $L_{Aeq.8h}$ of 75–85 dBA will help us establish an appropriate noise exposure limit that does not under- or over-estimate noise-induced hearing loss. To do this, a large dataset from workers exposed to a variety of industrial noise exposures with $L_{Aeq.8h}$ of 75–85 dBA needs to be collected.

Evidence shows that ethnicity could be one of the factors that may affect the expected distribution of pure-tone hearing thresholds. This dependence on ethnicity has prompted the development of national or regional datasets (Johansson & Arlinger 2004; Tambs et al. 2006; Flamme et al. 2011; Jun et al. 2015; Rodriguez Valiente et al. 2015; Flamme et al. 2020). Korea recently conducted the Korean National Health and Nutrition Examination Survey (KNHANES) 2010–2012 (Park et al. 2016). Median hearing thresholds between the KNHANES 2010–2012 and the USA National Health and Nutrition Examination Survey 1999–2004 were compared across age and sex, and no significant ethnic difference in hearing thresholds between the USA population and Korean population was found. Such a population-based dataset is not yet available for the Chinese population. Future studies would benefit from the inclusion of unexposed comparison groups on the examination of hearing thresholds.

CONCLUSION

The above data show that ISO 1999 underestimated NIPTS for both Gaussian and non-Gaussian noise exposure. The applicability of the ISO 1999 prediction model to different types of noise exposures needs to be reconsidered. Second, the kurtosis of noise plays an important role in evaluating the risk of NIHL. For a fixed energy level and exposure duration range, the noise-induced hearing loss increased as the kurtosis value of the noise increased. Finally, although acoustic energy is a necessary metric for the evaluation of noise environments for hearing conservation purposes, it may not be sufficient to characterize the risk to hearing. Energy and kurtosis may represent a necessary and sufficient set of metrics for such an evaluation. A better understanding of the role of the kurtosis metric in NIHL should lead to its incorporation into a new and more accurate method of noise exposure measurement and hearing risk assessment.

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OPEN

Estimation of Occupational Noise–Induced Hearing Loss Using Kurtosis-Adjusted Noise Exposure Levels

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Objectives: Studies have shown that in addition to energy, kurtosis plays an important role in the assessment of hearing loss caused by complex noise. The objective of this study was to investigate how to use noise recordings and audiometry collected from workers in industrial environments to find an optimal kurtosis-adjusted algorithm to better evaluate hearing loss caused by both continuous noise and complex noise.

Design: In this study, the combined effects of energy and kurtosis on noise-induced hearing loss (NIHL) were investigated using data collected from 2601 Chinese workers exposed to various industrial noises. The cohort was divided into three subgroups based on three kurtosis (β) levels (K_1: 3 ≤ β ≤ 10, K_2: 10 <β ≤ 50, and K_3: β > 50). Noise-induced permanent threshold shift at test frequencies 3, 4, and 6 kHz ($NIPTS_{346}$) was used as the indicator of NIHL. Predicted $NIPTS_{346}$ was calculated using the ISO 1999 model for each participant, and the actual NIPTS was obtained by correcting for age and sex using non-noise-exposed Chinese workers (n = 1297). A kurtosis-adjusted A-weighted sound pressure level normalized to a nominal 8-hour working day ($L_{Aeq,8h}$) was developed based on the kurtosis categorized group data sets using multiple linear regression. Using the $NIPTS_{346}$ and the $L_{Aeq,8h}$ metric, a dose-response relationship for three kurtosis groups was constructed, and the combined effect of noise level and kurtosis on NIHL was investigated.

Results: An optimal kurtosis-adjusted $L_{Aeq,8h}$ formula with a kurtosis adjustment coefficient of 6.5 was established by using the worker data. The kurtosis-adjusted $L_{Aeq,8h}$ better estimated hearing loss caused by various complex noises. The analysis of the dose-response relationships among the three kurtosis groups showed that the NIPTS of K_2 and K_3 groups was significantly higher than that of K_1 group in the range of 70 dBA ≤ $L_{Aeq,8h}$ < 85 dBA. For 85 dBA ≤ $L_{Aeq,8h}$ ≤ 95 dBA, the $NIPTS_{346}$ of the three groups showed an obvious $K_3 > K_2 > K_1$. For $L_{Aeq,8h}$ >95 dBA, the $NIPTS_{346}$ of the K_2 group tended to be consistent with that of the K_1 group, while the $NIPTS_{346}$ of the K_3 group was significantly larger than that of the K_1 and K_2 groups. When $L_{Aeq,8h}$ is below 70 dBA, neither continuous noise nor complex noise produced significant $NIPTS_{346}$.

Conclusions: Because non-Gaussian complex noise is ubiquitous in many industries, the temporal characteristics of noise (i.e., kurtosis) must be taken into account in evaluating occupational NIHL. A kurtosis-adjusted $L_{Aeq,8h}$ with an adjustment coefficient of 6.5 allows a more accurate prediction of high-frequency NIHL. Relying on a single value (i.e., 85 dBA) as a recommended exposure limit does not appear to be sufficient to protect the hearing of workers exposed to complex noise.

Key words: Complex noise, Impact/impulse noise, Kurtosis-adjusted noise exposure level, Kurtosis of noise, Noise-induced hearing loss, Noise-induced permanent hearing threshold.

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Researchers have long found that impulsive noise or complex noise with impulse/impact components is more hazardous to hearing than continuous steady state (Gaussian) noise at similar noise exposure levels (e.g., Nilsson et al. 1977; Evans and Ming 1982; Taylor et al. 1984; Theiry and Meyer-Bisch 1988; Lataye and Campo 1996). Current noise standards (such as ISO 1999) are based on hearing loss due to continuous steady-state noise. As a result, they underestimate the damage to hearing caused by non-Gaussian complex noise with equivalent sound pressure levels (Zhao et al. 2010; Zhang et al. 2021). Two earlier versions of the ISO 1999 document have mentioned corrections to the estimated noise exposure level to account for the increased hazard of noise with complex temporal characteristics, specifically noise containing impulsive components. The ISO 1999:1971 specified a correction of 10-dB, and the ISO 1999:1990 proposed a correction of 5-dB for impulsive/impact noise to compensate for the greater hazard of complex noise. However, the ISO 1999:2013 contained no mention of possible corrections. This may be due to the lack of a precise quantitative definition of impulse noise in previous versions, making such adjustments less feasible. Moreover, it has been found that for the same exposure level, complex noise can produce up to 30 to 40 dB more noise-induced hearing loss (NIHL) than Gaussian noise in animal models (Hamernik et al. 2003; Qiu et al. 2006, 2007). Thus, a 5- or 10-dB correction may not adequately address the greater hazard associated with non-Gaussian complex noise.

Complex noise consists of regular or irregular impulsive/impact components embedded in continuous Gaussian background noise and is very common in certain industrial (such as manufacturing and construction) and military settings. How to properly measure or characterize the great diversity of non-Gaussian noise found in industry is a challenging task. Erdreich (1986) proposed to use kurtosis to distinguish noise with impulsive components from steady-state noise. Inspired by Erdreich's work, Hamernik and his colleagues designed a series of animal (chinchilla) experiments in which different groups of animals were exposed to noise with the same energy but different kurtosis values (Lei et al. 1994; Hamernik et al. 2003, 2007; Qiu et al. 2006, 2007, 2013). The results show that for a fixed noise level, there is a monotonic relation between noise-induced hearing loss and kurtosis, and the hearing loss (defined as a permanent hearing threshold shift or loss of outer/inner hair cells) increases with the increase of kurtosis value. In other words, the kurtosis

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can differentiate the degree of hearing damage caused by noise with different temporal structures at the same noise exposure level in animals. These findings were also validated by human data in subsequent epidemiological studies (Zhao et al. 2010; Davis et al. 2012; Xie et al. 2016; Zhang et al. 2021). Although it is impossible to directly count hair cell loss in humans, noise-induced permanent hearing threshold shifts were verified in noise-exposed subjects.

Kurtosis is a statistical measure that defines how heavily the tails of distribution differ from the tails of a Gaussian distribution. For noise, kurtosis can be used to describe whether there is the presence of a high-amplitude sound (impact/impulse) that is different from the underlying continuous steady-state (Gaussian) noise and the degree of the impulsiveness of the noise (Qiu et al. 2020). A Gaussian noise has a kurtosis of 3. Noise with impulsive components embedded in Gaussian background noise will have kurtosis greater than 3. In general, the higher the kurtosis value, the stronger the noise impulsivity. It should be emphasized that kurtosis can only be used as an adjunct metric to energy in the assessment of NIHL. In other words, the application of kurtosis must be based on the energy of noise. If the equivalent sound pressure level of noise exposure is very low, then kurtosis has no effect on hearing loss (Qiu et al. 2006).

Goley et al. (2011) proposed a scheme to apply kurtosis to adjust the measured equivalent A-weighted, 8-hour, noise exposure level ($L_{Aeq,8h}$) with the equation as follows:

$$L'_{Aeq,8h} = L_{Aeq,8h} + \lambda log_{10} \frac{\beta_N}{\beta_G} \tag{1}$$

where β_N is the kurtosis of noise and β_G is the kurtosis of Gaussian noise, which is equal to 3. One of the most attractive features of the Goley et al. model is that it directly corrects the measured noise energy using the kurtosis of noise. It can be seen that using the kurtosis adjustment method is equivalent to adding a penalty, determined by the second term in the formula, to the overall sound pressure level ($L_{Aeq,8h}$). Because the kurtosis of complex noise (β_N) is higher than that of β_G, it has a positive correction term indicating that the risk of complex noise is higher. In the formula, λ is a key adjustment coefficient. Although the coefficient is not scaled in dB, the correction can be expressed that way. In the case of fixed noise kurtosis, it determines the degree of kurtosis adjustment for $L_{Aeq.8h}$. Goley et al. (2011) determined this coefficient to be 4.02 based on the results of animal (chinchilla) experiments. Due to the differences in the auditory system between animals and humans (such as the different frequency sensitivity range to sound) and the complexity of industrial noises in the real world, this coefficient may not be appropriate for humans. The validity of the adjustment factor for humans in the Goley model can only be validated by data from workers exposed to a variety of industrial noises.

In this study, we collected a large database of 3898 participants, including shift-long noise recordings and hearing levels of 2601 workers from various Chinese industries, and a control group of 1297 participants with no history of occupational noise exposure. The noise environments in these industries had a wide range of noise levels and kurtosis values that allowed for a comprehensive evaluation of the role of kurtosis in assessing NIHL. The objective of this study was to investigate how workers' and control data could be used to find an optimal adjustment coefficient (λ) for humans by studying the combined effects of noise level and kurtosis on high-frequency hearing loss, and to determine whether a kurtosis-adjusted $L_{Aeq,8h}$ using the Goley model improves the accuracy of prediction of hearing loss due to complex noise.

MATERIALS AND METHODS

This cross-sectional study was conducted in Zhejiang and Jiangsu provinces, eastern China. The study protocol was approved by the Ethics Committee of Zhejiang and Jiangsu Provincial Centers for Disease Control and Prevention (approval reference number: ZJCDC-T-043-R and JSCDCLL-2017-025).

Recruitment of Participants

A total of 4916 subjects were initially introduced to the purpose of the study and invited to participate between 2008 and 2018. This cohort included 3244 noise-exposed and 1672 non-noise-exposed workers. All participants signed an informed consent form. For inclusion in the study, all participants had to satisfy the following three criteria: (1) no history of genetic or drug-related hearing loss, head wounds, or ear diseases; (2) no history of military service or shooting activities; and (3) good conditions of the external auditory canal, tympanic membrane, and the middle ear on otoscopic examination. Noise-exposed participants needed to satisfy additional criteria: (1) consistently worked in the same job category and at the same worksite (noise exposure area) for the period from the beginning of a worker's career to the date of the investigation; (2) a minimum of at least one year of employment in their current position; (3) having an A-weighted noise exposure level (L_{Aeq}) at their jobs between 70 and 95 dBA. As a result, a total of 2601 noise-exposed participants and 1297 non-noise-exposed participants (control) were included from the original pool of 3244 and 1672, respectively.

The reason for choosing workers exposed to $L_{Aeq.8h}$ between 70 and 95 dBA is that a previous study (Zhang et al. 2021) indicated that the recommended exposure limit of 85 dBA, as an 8-hour time-weighted average (NIOSH 1998), may not be a safe noise exposure limit, especially for complex noise with impulsive components and, therefore, it may be necessary to observe the biological effects of lower noise exposure levels on hearing. It was observed that when the $L_{Aeq,8h}$ was less than 95 dBA, workers rarely used hearing protection devices; when the noise $L_{Aeq,8h}$ was equal to or greater than 95 dBA, the proportion of hearing protection devices used increased significantly. Because an accurate unprotected dose-response relationship is the basis of this study, we needed to exclude data of workers exposed to higher than 95 dBA.

Most participants still did not use a hearing protection device (HPD) despite the implementation of hearing conservation programs on a wide scale in China starting in 2012. The use of HPDs, usually earplugs, both on and off the job, was assessed through field observations by the researchers and in the questionnaire and reported to be low and infrequent. At high noise exposure levels, that is, ~95 dBA and above, the use of HPDs was observed to be sporadic. The inclusion of these participants would, to some extent, have an effect on the relationship between noise level and noise-induced permanent threshold shift (NIPTS). We expected this effect to occur primarily in the participants exposed to noise above 95 dBA. For those participants who have never used HPDs, the members of the research team recommended the use of appropriate HPDs after data collection. During this study, workers in the investigated factories received training on how to properly use HPDs.

Questionnaire Survey

All participants were required to complete a noise exposure and health questionnaire, which was followed by a face-to-face interview by an occupational hygienist for quality control. The questionnaire included the following information: general demographic information (age, sex, etc.); occupational history (factory, worksite, job description, length of employment, duration of daily noise exposure, and history of using hearing protection); and overall health status (including any history of ear disease and/or ototoxic drug exposure).

Audiometric Evaluation

Each participant underwent an otologic and audiometric examination. Otoscopy was carried out initially to ensure participants had no external ear abnormalities. Air conduction pure-tone hearing threshold levels were tested at 0.5, 1, 2, 3, 4, 6, and 8 kHz in each ear by an experienced audiologist. Testing was conducted in a double-walled audiometric booth using an audiometer (Madsen OB40, Denmark) with an air conduction headphone (Sennheiser HDA 300). The tests were conducted manually, and the measurement was based on the threshold determination methods of the American Speech-hearing-Language Association (ASHA 2005). Before the implementation of the project, the audiometer and headphone were calibrated by the Zhejiang Institute of Metrology of China, according to the Chinese national standard (GB4854-84). During the duration of the project, a bioacoustic check and a listening check of the headphone were performed daily. The noise floor of the booth was compliant with ANSI S3.1-1999 specifications from 125 to 8000 Hz (ANSI 2008). Audiograms were measured at least 16 hours after the participants' last occupational noise exposure.

Noise Data Collection

A digital noise recorder (ASV5910-R, Hangzhou Aihua Instruments Co., Ltd., China) was used to record a shift-long personal noise exposure for each participant. The instrument uses a ¼-inch pre-polarized condenser microphone with a broad response frequency (20 to 20 kHz) and high-sensitivity level (2.24 mV/Pa). The measurement ranges from 40 dB(A) to 141 dB(A). The recorder can work continuously for 23 hours under full charge. One full-shift recording of each participant's noise exposure was captured by the ASV5910-R at 32-bit resolution with a 48-kHz sampling rate and saved in a raw audio format (WAV file). The noise record was saved on a 32 GB micro SD card and transferred to a portable hard disk for subsequent analysis. It was performed one time for each participant. Before recording, a hygienist confirmed with each participant that this was the noise they were typically exposed to on an average working day. The members of the research team monitored the noise collection of individual participants in the workplace. The microphone was placed on the shoulder of each participant at the start of the work shift and collected at the end of the shift. The participants were trained to wear the recorder properly.

Calculation of Noise Metrics

Two noise metrics were used in this study: (1) the A-weighted equivalent sound pressure level normalized to a nominal 8-hour working day ($L_{Aeq,8h}$); (2) the kurtosis of noise exposure (β_N). A program using MATLAB (The MathWorks, R2017) software was developed for analyzing the full-shift noise waveforms that were collected on each participant. The program was designed to extract the $L_{Aeq,8h,}$ and kurtosis, i.e.,

(1) $L_{Aeq,8h}$ level, in A-weighted decibels, is given by the formula (ISO 1999, 2013):

$$L_{Aeq,8h} = L_{Aeq,T_e} + 10\log(T_e / T_0) \tag{2}$$

where $L_{Aeq,Te}$ is the A-weighted equivalent continuous sound pressure level for T_e; T_e is the effective duration of the working day in hours, and T_0 is the reference duration (T_0 = 8-hour).

(2) Calculation of the kurtosis of noise exposure in a typical work day (β_N)

The kurtosis of the recorded noise signal was computed over consecutive 60-second time windows without overlap over the shift-long noise record using a sampling rate of 48 kHz for noise recording (Tian et al. 2021). For a sample of *N* values, the kurtosis is calculated as:

$$\beta = \frac{1}{N}\sum\nolimits_{i=1}^{n}(x_i-\bar{x})^4 \Big/ \left(\frac{1}{N}\sum\nolimits_{i=1}^{n}(x_i-\bar{x})^2\right)^2 \tag{3}$$

where x_i is the i^{th} value of noise amplitude and $\bar{x}$ is the sample mean. The average of the measured kurtosis values (β_j) at every 60 seconds is used as the kurtosis of noise exposure (β_N), which is calculated as

$$\beta_N = \frac{1}{N}\sum\nolimits_{j=1}^{N}\beta_j \tag{4}$$

where *N* is the number of kurtosis values of the full-shift noise exposure.

Noise-Induced Permanent Threshold Shift Estimation

The analysis focused on the noise-sensitive frequency range of 3 to 6 kHz because the noise-induced hearing loss from continuous noise occurs predominantly in this range initially (Lie et al. 2016). The actual NIPTS for each noise-exposed participant at test frequencies 3, 4, and 6 kHz were obtained by subtracting normal median hearing threshold levels by age- and sex-matched populations of the control group collected in this study. The thresholds of the better ear were determined for all participants across the test frequencies. The better ear was used because this was the criteria for establishing median hearing threshold levels of the control group in ISO 1999:2013 (Hoffman et al. 2010). Because the participants were typically exposed to only one type of high-level occupational noise throughout their working life, and since their working environments were consistent over the course of their employment, the observed hearing-loss estimates were likely attributable to the measured industrial noise exposures.

The actual value of NIPTS of each individual participant was compared with the median NIPTS predicted by ISO 1999

(2013), and the accuracy of ISO 1999 predictions for NIPTS was evaluated statistically. The ISO 1999 median NIPTS prediction for each participant was determined using the equations described in the ISO 1999 document as follows:

$$NIPTS = \begin{cases} \left[u + v\log\left(\frac{t}{t_0}\right) \right] \left(L_{Aeq,8h} - L_0\right)^2, & 10 \le t \le 40 \\ \frac{\log(t+1)}{\log(11)} \left[u + v\log\left(\frac{10}{t_0}\right) \right] \left(L_{Aeq,8h} - L_0\right)^2, & t < 10 \end{cases} \quad (5)$$

where $L_{Aeq,8h}$ is the noise exposure level normalized to a nominal 8-hour working day; t is noise exposure duration in years, $t_0 = 1$ year; L_0 is the reference sound pressure level in Table 1 of ISO 1999 (2013); u and v are coefficients given as a function of audiometric test frequency in Table 1 of ISO 1999 (2013).

Kurtosis Categories

To analyze the effect of kurtosis on NIPTS, we grouped the data according to the noise kurtosis value (β_N) that each worker was exposed to. The kurtosis group should be divided so that the mean NIPTS of workers within this group is significantly different from that of other groups. The participants were partitioned into one of three groups based on the kurtosis value of their noise exposure:

1. K_1: $3 \le \beta_N \le 10$;
2. K_2: $10 < \beta_N \le 50$;
3. K_3: $\beta_N > 50$

Based on our analysis of individual noise data collected from more than 3000 workers, the kurtosis of industrial noise can be as high as about 1000. More details on the kurtosis grouping described above are available in the Discussion section.

Kurtosis-Adjusted $L_{Aeq,8h}$

The kurtosis adjustment was calculated according to Eq. 1 (Goley et al. 2011). Taking actual NIPTS as the dependent variable and $L_{Aeq,8h}$ and $\log_{10}(\beta_N/3)$ as independent variables, the coefficient λ was calculated by multiple linear regression model:

$$\text{NIPTS} = b_0 + b_1 L_{Aeq,8h} + b_2 log_{10}\left(\beta_N / 3\right) + \varepsilon \quad (6)$$

where b_0 is the NIPTS-intercept; b_1 and b_2 are the regression coefficients representing the change in NIPTS relative to a one-unit change in $L_{Aeq,8h}$ and $log_{10}(\beta_N/3)$, respectively; ε is the model's random error (residual) term. The regression analysis obtains the optimal values for b_0, b_1, and b_2 that minimizes ε, and $\lambda = b_2/b_1$. The dependent variable is actual $NIPTS_{346}$, that is, the average of actual NIPTS at 3, 4, and 6 kHz. The model was validated by comparing the difference between actual $NIPTS_{346}$ and estimated $NIPTS_{346}$ (with or without kurtosis adjustment) using the ISO 1999:2013 formula.

Statistical Analysis

Noise exposure level ($L_{Aeq,8h}$), duration of exposure, kurtosis, age, and sex were summarized in Table 2 as count, mean, and standard deviation or range (minimum to maximum). The actual measured $NIPTS_{346}$ and the difference between the actual $NIPTS_{346}$ and the ISO 1999 predicted $NIPTS_{346}$ were analyzed using a mixed model where the $NIPTS_{346}$ or the $NIPTS_{346}$ difference served as the dependent variable, and noise level ($L_{Aeq,8h}$), kurtosis, and their interaction served as independent variables. The group means for noise level and kurtosis, and their 95% confidence interval (CI) were calculated. A significance level of $p < 0.05$ was applied to the overall test for all factors and their interaction. Pairwise comparisons were processed among $NIPTS_{346}$ and kurtosis groups. For all pairwise comparisons, Bonferroni adjustment was applied in evaluating significance. The analyses were performed using IBM® SPSS Statistics (version 22).

RESULTS

Demographics of Experimental Groups

The 1297 participants in the control group had no history of exposure to high-level workplace noise. They are factory office workers, technology company programmers, and health care workers working in environments with noise levels below 70 dBA. Table 1 shows selected values of the statistical distribution of hearing threshold levels in decibels of the control group according to frequency classified by age and sex. The median hearing thresholds were used to estimate the actual NIPTS of noise-exposed workers.

Data were collected on 2601 workers exposed to various industrial noises. The workers were classified into three groups according to the kurtosis value of noise they were exposed to. Table 2 presents a breakdown of typical noise sources, sex, average age, noise exposure level, and exposure duration corresponding to workers in three noise kurtosis categories.

Scatter Plots of $NIPTS_{346}$ Raw Data

Some perspective on the relationship between $NIPTS_{346}$ and $L_{Aeq,8h}$ can be obtained by plotting actual $NIPTS_{346}$ for each noise exposure level (from 70 to 95 dBA). Figure 1 shows the resulting scatter plot for the entire data pool of noise-exposed workers (n = 2601). Large variations were observed for each kurtosis category across the $L_{Aeq,8h}$ range.

The effects of different kurtosis categories are evident when the noise exposure level ($L_{Aeq,8h}$) measurements are collapsed into 1-dB bins, and the mean noise level within each bin is plotted against the mean actual $NIPTS_{346}$ for that bin. These effects are shown in Figure 2. In this figure, the abscissa represents the mean $L_{Aeq,8h}$, and the ordinate is the mean $NIPTS_{346}$ for the data points belonging to a specific kurtosis category within the 1-dB bin. The figure clearly shows a positive relationship between the $L_{Aeq,8h}$ and $NIPTS_{346}$ for each kurtosis category. Because the data shown in Fig. 2 suggest both linear and nonlinear relations among the $L_{Aeq,8h}$ and $NIPTS_{346}$, a logistic function that would allow nonlinear and nearly linear descriptions of the data of the form NIPTS = $a/[1+e^{(b-LAeq)/c}]$ was chosen to describe the results of the three kurtosis categories. For the appropriately set parameters a, b, and c, this relation allows NIPTS to approach a positive number close to zero as $L_{Aeq,8h}$ approaches 0 dBA, and NIPTS to a ceiling value as $L_{Aeq,8h}$ approaches a high level (e.g., greater than 95 dBA). Note: As can be seen in Figure 1, for the K_1 group (solid black circles), due to the small sample size of $L_{Aeq,8h}$ when it is less than 80 dBA, there are not enough samples in the 1-dB interval, so the samples of $L_{Aeq,8h}$ in the 70 to 79 dBA region are divided into two groups to ensure a certain number of samples in each group. The samples of $L_{Aeq,8h}$ in the range of 70 to 75 dBA were averaged to get an average point, and the

TABLE 1. Selected values of the statistical distribution of hearing threshold levels in decibels of the control group according to frequency classified by age and sex

	Hearing Threshold Level (dB)														
	Age* (yrs)														
	20			30			40			50			60		
	Percentages														
Frequency (Hz)	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
Male															
500	3	6	10	–1	6	12	0	6	13	1	8	15	3	11	17
1000	1	6	12	–2	4	11	–2	6	15	1	7	15	2	9	17
2000	–2	4	11	–2	4	12	–2	6	15	0	8	18	2	13	24
3000	1	5	12	–2	6	12	–2	8	19	1	11	12	5	15	32
4000	–3	6	12	–3	5	12	–3	8	18	4	13	26	–2	15	41
6000	3	12	25	4	13	25	4	17	28	10	23	44	14	28	57
Female															
500	2	6	12	–1	5	11	0	6	13	2	8	15	4	12	25
1000	0	6	12	–2	4	11	–2	5	13	0	7	17	4	12	27
2000	–1	5	12	–2	5	12	–2	5	13	2	9	18	5	14	27
3000	–2	5	12	–2	5	13	–2	6	16	1	10	18	5	19	34
4000	–3	4	12	–4	3	12	–4	5	15	–1	8	17	3	19	34
6000	7	13	22	3	13	21	3	15	27	8	19	33	11	31	52

Age is grouped in 10-yr intervals; that is, "30" represents ages 25 to 34 yrs, etc.

data samples in the range of 76 to 79 dBA were averaged to get another data point, as shown in Figure 2. Similarly, for the K_3 group (hollow red circles in Fig. 1), sample averages within the range of 70 to 75 dBA and 76 to 78 dBA were taken to obtain two data points with $L_{Aeq,8h}$ less than 79 dBA in the K_3 group. For the K_2 group (hollow green circles in Fig. 1), since there are enough sample points at each 1-dB interval, all the average points in Figure 2 can be obtained by averaging the sample points at each 1-dB interval.

Multiple Linear Regression

Initially, the regression analyses used the average NIPTS at 3, 4, and 6 kHz as the dependent variable, with age, sex, duration, $L_{Aeq,8h,}$ and $\log_{10}(\beta_N/3)$ as the independent variables. As mentioned above, actual NIPTS of each noise-exposed worker were obtained by subtracting normal median hearing threshold levels by age- and sex-matched populations of the control group. As a result, the correlation between NIPTS and age or sex was reduced. The inclusion of age and sex as independent variables did not significantly improve the model fitting using the multiple linear regression analysis. The data points in Figure 2 were used for multiple regression. As shown in Figure 2, the 1-dB bin analysis method highlighted the relationship between $L_{Aeq.8h}$ and $NIPTS_{346}$ functions under each kurtosis category but smoothened out the influence of exposure duration on exposure duration multiple linear regression. Consequently, the inclusion of the duration as an independent variable did not significantly improve the model's performance. Eventually, $L_{Aeq.8h}$ and $\log_{10}(\beta_N/3)$ were used as independent variables of the multiple linear regression equation, controlling for the effects of age, sex, and exposure duration. Table 3 shows the results of two regression models, one using $L_{Aeq,8h}$ as the exposure variable and the other using the kurtosis-adjusted $L_{Aeq,8h}$. It is clear from Table 3 that the $L_{Aeq,8h}$ alone (Model 1 in Table 3) is a fairly strong predictor of hearing loss with a coefficient of determination $R^2 = 0.75$, whereas the kurtosis-adjusted model (Model 2 in Table 3) has an $R^2 = 0.88$ (an increase of 0.13 over the R^2 value in Model 1). The difference in R^2 between the two models is significant ($p < 0.001$). This significant change in the overall model fit indicates that the model attribution of hearing loss has an important change from $L_{Aeq,8h}$ to kurtosis-adjusted $L_{Aeq,8h}$ (i.e., $L'_{Aeq,8h}$). In other words, the kurtosis-adjusted $L_{Aeq,8h}$ can significantly improve the accuracy of noise-induced hearing loss assessment. Using the human data collected in China, the coefficients b_1 and b_2 in Model 2 were obtained as 0.56 and 3.64, respectively. Consequently, the adjustment coefficient can be calculated as $\lambda = b_2/b_1 = 6.50$.

TABLE 2. A breakdown of typical noise sources, sex, average age, noise exposure level, and exposure duration corresponding to workers in three noise kurtosis categories

		Participants			Noise Exposure	
Kurtosis Category	Typical Noise Sources	Male (n)	Female (n)	Age (yrs)	Duration (yrs)	L_{Aeq} (dBA)
$3 \le \beta_N \le 10$	Spinning, weaving, pulping	377	140	36.4 ± 9.4	9.9 ± 7.6	88.6 ± 4.6
$10 < \beta_N \le 50$	Punching, stamping, metalworking, heat treating, assembly, drilling	1125	412	36.3 ± 9.0	9.7 ± 7.8	87.2 ± 5.1
$\beta_N > 50$	Woodworking, nail gunning, assembly	463	84	34.6 ± 9.9	6.5 ± 6.5	87.9 ± 4.8

Note: age, duration, and L_{Aeq}: mean±1 SD.

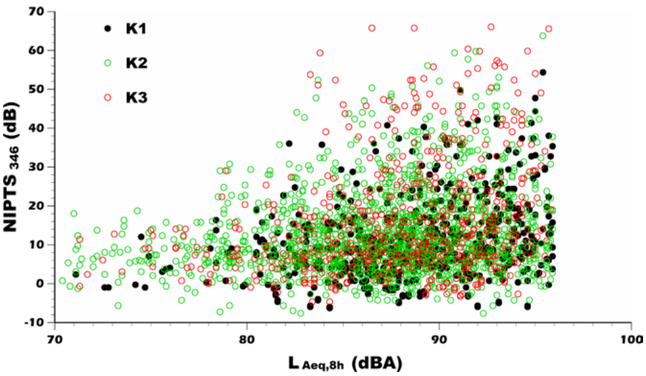

Fig. 1. Scatter plot showing noise-induced hearing loss ($NIPTS_{346}$) as a function of noise exposure level $L_{Aeq,8h}$. The kurtosis value ranges are K_1:3 ≤ β_N ≤ 10; K_2: 10 < β_N ≤ 50; K_3: β_N > 50.

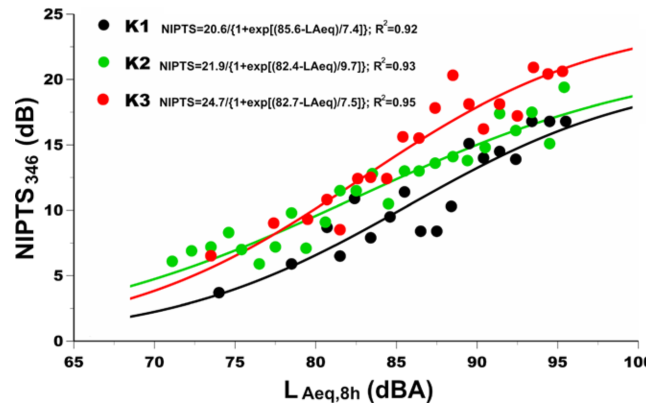

Fig. 2. Scatterplot showing noise-induced hearing loss ($NIPTS_{346}$) as a logistic function of noise exposure level $L_{Aeq,8h}$, and kurtosis category using 1-dB noise-level bins. The kurtosis value ranges are K_1:3 ≤ β_N ≤ 10; K_2: 10 < β_N ≤ 50; K_3: β_N > 50.

Application of Kurtosis-Adjusted $L_{Aeq,8h}$ to the Estimation of NIPTS

The kurtosis-adjusted $L_{Aeq,8h}$ (i.e., $L'_{Aeq,8h}$) was used to estimate $NIPTS_{346}$, and the results were compared with those from unadjusted $L_{Aeq,8h}$. According to the above multiple linear regression results, the following equation was used for $L'_{Aeq,8h}$:

$$L'_{Aeq,8h} = L_{Aeq,8h} + 6.5 * log_{10}(\beta_N / 3) \quad (7)$$

The $NIPTS_{346}$ of each individual noise-exposed worker was estimated by ISO prediction formula [Eq. (5)] using either $L_{Aeq,8h}$ (un-adjusted) or $L'_{Aeq,8h}$ (kurtosis-adjusted). The values of estimated $NIPTS_{346}$ using $L_{Aeq,8h}$ or $L'_{Aeq,8h}$ were compared with corresponding actual $NIPTS_{346}$, respectively. The mixed model analysis showed that there was a significant adjustment effect (df = 1, F = 346.6, p < 0.001), and kurtosis by adjustment interaction effect (df = 2, F = 40.3, p < 0.001) on the $NIPTS_{346}$ difference. The estimated marginal mean (EMM) for each group is summarized in Table 4.

Figure 3 displays the EMM of underestimated $NIPTS_{346}$ for each kurtosis level before and after kurtosis adjustment. The results show that, for unadjusted $L_{Aeq,8h}$, the ISO 1999 formula underestimates $NIPTS_{346}$ by an average of 3.72 dB for kurtosis group K_1; by 6.35 dB for group K_2; 10.24 dB for group K_3. After the noise levels ($L_{Aeq,8h}$) were adjusted for kurtosis using Equation 7, the ISO 1999 predictions underestimated NIPTS by an average within 1.23 dB for kurtosis group K_1; within 0.08 dB for group K_2; and within -0.96 dB for group K_3. Figure 3 demonstrates that a kurtosis-adjusted noise exposure level (i.e., $L'_{Aeq,8h}$) using adjustment coefficient of λ = 6.5 can effectively correct the ISO formula's underestimates due to complex noise with high kurtosis values. As a comparison, another adjustment coefficient λ = 4.02, derived from chinchilla data by Goley et al. (2011), was used to calculate kurtosis-adjusted $L_{Aeq,8h}$. The EMM of underestimated $NIPTS_{346}$ for each kurtosis level after kurtosis adjustment using λ = 4.02 was also shown in Figure 3. The results showed that after the noise levels were adjusted for kurtosis using λ = 4.02, the ISO 1999 predictions underestimated NIPTS by an average of 1.6 dB for kurtosis group K_1; by 2.8 dB for group K_2; and by 4.5 dB for group K_3. While kurtosis-adjusted $L_{Aeq,8h}$ using λ = 4.02 could correct underestimations of NIHL due to complex noise exposure to a certain extent, its correction degree is insufficient for human data.

DISCUSSION

The Classification of Noise Kurtosis

One method to analyze the effect of kurtosis on NIHL is to make a reasonable clustering of data according to the kurtosis values of noise exposed by individual workers and then compare the differences of $NIPTS_{346}$ in each data class under a similar noise level. The data used in this study between 85 and 95 dBA are the same as those used in the previous study (Zhang et al, 2021). The kurtosis (β) was classified into four categories in Zhang's study (2021), that is, $3 \le \beta \le 10$ (K_1^*), $10 < \beta \le 30$ (K_2^*), $30 < \beta \le 75$ (K_3^*), and $\beta > 75$ (K_4^*). In this study, we initially divided data into the same four categories as above. Figure 4A shows the EMM of $NIPTS_{346}$ obtained from these four groups. For group K_1^*, the EMM of $NIPTS_{346}$ was 11.5 dB, which was significantly lower than the 13.4 dB in group K_2^* (p = 0.01), the 14.1dB in group K_3^* (p = 0.001), and the 17.3 dB in group K_4^* (p < 0.001). There was no significant difference in $NIPTS_{346}$ between group K_2^* and group K_3^* (p = 0.24), but their EMMs of $NIPTS_{346}$ were significantly smaller than that of group K_4^* (p < 0.001 for both K_2^* - K_4^* and K_3^* - K_4^* group pairs). Thus, the groups K_2^* and K_3^* can be considered to be merged as one group. Due to the high kurtosis values that were included in group K_3^* and the large span of this group, group K_3^* was further divided into two subgroups:$30 < \beta \le 50$ ($K_{3\_1}^*$) and $50 < \beta \le 75$ ($K_{3\_2}^*$), as shown in Fig. 4B. The EMM of $NIPTS_{346}$ in group $K_{3\_1}^*$ was 13.5 dB, which was very close to that of group K_2^* (p = 0.9), while EMM of $NIPTS_{346}$ in group $K_{3\_2}^*$ was 15.8 dB, which was significantly higher than that of group $K_{3\_1}^*$ (p = 0.03), but there was no significant difference between group K_4^* and group $K_{3\_1}^*$ (p = 0.06). Thus, it is reasonable to merge K_2^* and $K_{3\_1}^*$ into one group and merge $K_{3\_2}^*$ and K_4^* into another group. Eventually, the three groups of kurtosis were classified as shown in Figure 4C, that is, $3 \le \beta \le 10$ (K_1);$10 < \beta \le 50$ (K_2), and $\beta \ge 50$ (K_3). The EMMs of $NIPTS_{346}$ in these three groups were 11.5, 13.4 dB, and 16.6 dB, respectively. The $NIPTS_{346}$ differences among these three groups were statistically significant, with p values as follows: p = 0.007 for K_1- K_2 group pair, p < 0.001 for K_1 to K_3 and K_2 to K_3 group pairs. Based on the above kurtosis classification, the combined effects of noise level and kurtosis on high-frequency NIPTS were analyzed, and the Goley model was studied.

TABLE 3. Results of regression models using $L_{Aeq,8h}$ and kurtosis-adjusted $L_{Aeq,8h}$ to estimate $NIPTS_{346}$

	Coefficients B	λ (b_2/b_1)	*t* Stat	*p* value	B Lower 95%	B Upper 95%
Model 1: $NIPTS_{346} = b_0+b_1L_{Aeq,8h}$		N/A			R^2 = 0.75	F = 182.20
Intercept	–36.25		–10.02	<0.0001	–43.30	–29.02
L_{Aeq}	0.57		13.50	<0.0001	0.49	0.66
Model 2: $NIPTS_{346} = b_0+b_1L_{Aeq,8h}+b_2\log_{10}(\beta_N/3)$		6.50			R^2 = 0.88	F = 225.81
Intercept	–38.64		–15.41	<0.0001	–43.66	–33.62
L_{Aeq}	0.56		19.31	<0.0001	0.50	0.62
$\log_{10}(\beta_N/3)$	3.64		8.22	<0.0001	2.79	4.40

Note: the effects of age, sex, and duration were controlled in the models.

Types of Work and Their Kurtosis Distributions

Table 5 displays the kurtosis distribution information of some work tasks in the manufacturing industry and corresponding correction values for measured $L_{Aeq,8h}$. The kurtosis value of a work type in Table 5 was calculated by averaging the kurtosis of individuals of the same work type. The correction value was calculated by $6.5*\log_{10}(\beta/3)$. Table 5 lists the mean, standard deviation, and maximum and minimum values of each work type's kurtosis values. As shown in Table 5, the primary sources of steady-state noise are textile mills and paper mills. However, non-Gaussian complex noise is more common than steady-state noise in the manufacturing industry. Among these noises, the complex noise with a kurtosis of $10 < \beta_N \leq 50$ accounts for the majority, such as stamping, drilling, casting, metal processing, etc. In this study, the highly impulsive complex noises ($\beta_N > 50$) mainly existed in the workplaces of wood processing, nail gunning, and assembly in various manufacturing plants (including automobile, furniture, and electronic machinery manufacturers). It is worth noting that many work types have a wide range of kurtosis values, some spanning two kurtosis categories, some even three kurtosis categories. Examples include stamping, drilling, casting, metalworking, etc., with kurtosis values ranging from 7 to 86. The kurtosis and level of noise received by individual workers can largely depend on such factors as the position of work, the frequency of tool use, and the intensity of background noise. Therefore, the kurtosis of the noise exposure of individual workers should be calculated according to the actual noise exposed for each worker.

In this study, most workers did not wear hearing protection devices, and a small population of workers with high noise exposure (L_{Aeq}~95 dBA) may wear devices. A recent study of 385 workers at an automobile manufacturing plant in China (Gong et al. 2021) found that earplug use had no significant effect on the prevalence of high-frequency hearing loss among study participants, despite the requirement to wear earplugs at all times during work. There are many reasons for this, such as poor training, poor fit, and workers not wearing earplugs all the time. Workers in this study had the same problem even when they used earplugs. Therefore, the overall reliability of the dose-response relationship was not affected by the fact that very few people in this data had worn earplugs.

Based on the data analysis of 2601 workers in this study, 19.9% of workers were exposed to steady-state noise ($3 \leq \beta_N \leq 10$), 59.1% of workers to complex noise with low or moderate impulsive components ($10 < \beta_N \leq 50$), and 21% of workers to complex noise with high kurtosis ($\beta_N > 50$). Because non-Gaussian complex noise is common in the manufacturing industry, and the current noise standards (e.g., ISO 1999:2013) are based solely on steady-state noise data, kurtosis adjustment is a promising method to correct the noise level so as to accurately identify the risk of NIHL.

The Combined Effect of Noise Level and Kurtosis on NIHL

A logistic function was used to fit the dose-response data shown in Figure 2 for three kurtosis categories. The general expression of the logistic function is as follows:

$$NIPTS_{346} = a \Big/ \left(1+e^{(b-L_{Aeq,8h})/c}\right) \quad (8)$$

Figure 2 shows that there was a good relationship between $L_{Aeq,8h}$ and $NIPTS_{346}$ using logistic function fitting in each

TABLE 4. The estimated marginal means and standard errors of $NIPTS_{346}$ difference between the actual measured $NIPTS_{346}$ and the ISO 1999 predicted $NIPTS_{346}$ for BAA and kurtosis by BAA groups

				95% Confidence Interval	
Effect	Group	Estimated Mean	Standard Error	Lower Bound	Upper Bound
BAA*	Unadjusted (UA)	6.77	0.26	6.27	7.27
	KA	0.03	0.26	–0.47	0.53
Kurtosis×BAA†	K_1×KA	1.23	0.51	0.23	2.23
	K_1×UA	3.72	0.51	2.73	4.72
	K_2×KA	0.08	0.29	–0.50	0.66
	K_2×UA	6.35	0.29	5.77	6.92
	K_3×KA	–0.96	0.49	–1.93	0
	K_3×UA	10.24	0.49	9.27	11.21

BAA, before-and-after-adjustment; KA, Kurtosis-adjusted.
**p value for $NIPTS_{346}$ difference between KA and UA is <0.001.*
†p values for $NIPTS_{346}$ difference between (K_i×KA) and (K_i×UA) pairs (i = 1, 2, and 3) are <0.001.

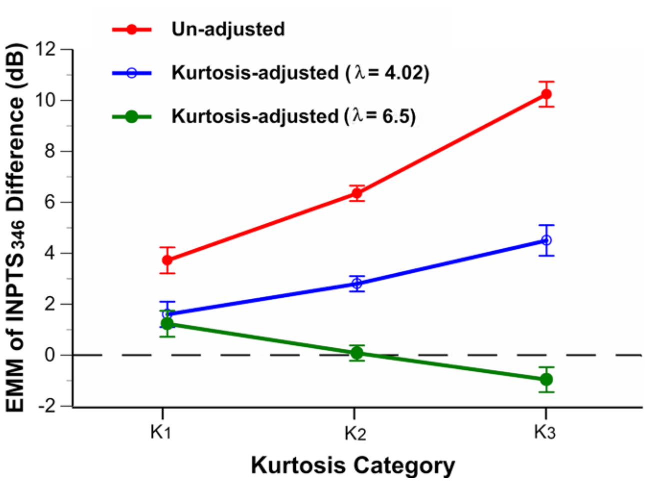

Fig. 3. The estimated marginal mean of underestimated $NIPTS_{346}$ by ISO 1999:2013 model for three kurtosis levels under un-adjusted and kurtosis-adjusted noise levels. Error bars: standard error. The kurtosis value ranges are K_1:3 ≤ β_N ≤10; K_2: 10 < β_N ≤ 50; K_3: β_N > 50.

kurtosis category (coefficient of determination $R^2 > 0.9$ for all three curves). For the sake of discussion, the three equations reflecting $L_{Aeq,8h}$ and $NIPTS_{346}$ were named after the kurtosis category, which is the K_1 curve, K_2 curve, and K_3 curve, respectively.

The K_1 curve (the black line) in Figure 2 reflects the relationship between continuous steady-state noise and high-frequency hearing loss ($NIPTS_{346}$), and its fitting curve equation is $NIPTS_{346} = 20.6 / [1 + e^{(85.6 - L_{Aeq,8h})/7.4}]$. Based on this equation, the $NIPTS_{346}$ can be calculated when $L_{Aeq,8h}$ is at a specific level. Considering the situation when $L_{Aeq,8h}$ = 75 dBA, where the calculated value of $NIPTS_{346}$ is 3.9 dB, this is very close to the actual value (i.e., 3.7 dB at $L_{Aeq,8h}$ = 74 dBA) in Fig. 2. When $L_{Aeq,8h}$ = 78 dBA, the calculated $NIPTS_{346}$ is 5.4 dB, showing an increased hearing shift (hearing loss) at the high frequencies, which is consistent with ISO 1999:2013. The ISO 1999:2013 specifies a damage risk threshold $L_{Aeq,8h}$ equal to 75 dBA (at 4 kHz); however, NIPTS is not predicted until the exposure level reaches 78 dBA. When $L_{Aeq,8h}$ = 80 dBA, the calculated value of $NIPTS_{346}$ will be 6.6 dBA according to the K_1 curve. The exposure level of 80 dBA was set as the action level (need to wear hearing protection devices) by the European Union (Directive 2003/10/EC). When the $L_{Aeq,8h}$ equals 85 dBA, the calculated $NIPTS_{346}$ is 9.9 dB. High-frequency hearing loss is apparent at this level. This level was set as recommended exposure level (REL) by the US National Institute for Occupational Safety and Health (NIOSH 1998) and Action Level by the U.S. Occupational Safety and Health Administration (OSHA 1983).

The K_2 curve (the green line) in Figure 2 presents the relationship between non-Gaussian noise with low or moderate impulsive components (10 < β ≤ 50) and high-frequency hearing loss ($NIPTS_{346}$). The equation of this curve is: $NIPTS_{346} = 21.9 / [1 + e^{(82.4 - L_{Aeq,8h})/9.7}]$. As shown in Figure 2, when $L_{Aeq,8h}$ = 70 dBA, the calculated value of $NIPTS_{346}$ is 4.7 dB. When the $L_{Aeq,8h}$ is 75 dBA, the calculated value of $NIPTS_{346}$ is 7 dB. From Figure 2, it can be seen that the actual $NIPTS_{346}$ values of group K_2 were all about 7 dB within the range of 72 to 77 dBA, which is near twice the magnitude of the shifts at this level in group K_1. When the $L_{Aeq,8h}$ equals 80 dB, the calculated value of $NIPTS_{346}$ is 9.6 dB, indicating that the non-Gaussian complex noise had begun to produce significant $NIPTS_{346}$ at this exposure level. It is worth noting that when the exposure level of complex noise is 80 dBA, and the kurtosis value was greater than ten and less than 50, the high-frequency hearing loss caused by complex noise is comparable to that induced by continuous steady state noise at 85 dBA ($NIPTS_{346}$ = 9.6 versus 9.9 dB). Therefore, for complex noise (β > 10), the NIOSH noise exposure REL and OSHA Action Level may need to be lowered from 85 dBA to 80 dBA in the United States and elsewhere. It is worth noting that Smoorenburg (2003) suggested an exposure limit of 80 dBA for impulse sounds. An interesting trend in the K_1 and K_2 curves is that they converge $L_{Aeq,8h}$ increases. When $L_{Aeq,8h}$ ≥100 dB, the difference of $NIPTS_{346}$ between the curves is only 0.3 dB. This convergence suggests that hearing loss from complex noise with moderate kurtosis values (10 < β ≤ 50) tends to produce a comparable level of hearing loss when the noise level reaches a fairly high level (100 dBA). However, when $L_{Aeq,8h}$ was less than 100 dBA, especially in the range of 70 to 90 dBA, for a fixed exposure level, the $NIPTS_{346}$ in group K_2 was significantly higher than that in group K_1.

The K_3 curve (the red line) in Figure 2 demonstrates the relationship between $NIPTS_{346}$ and complex noise with high kurtosis values (β > 50). The fitting curve equation is as follows: $NIPTS_{346} = 24.7 / [1 + e^{(82.7 - L_{Aeq,8h})/7.5}]$. When $L_{Aeq,8h}$ is equal to 70 dBA, the calculated value of $NIPTS_{346}$ is 3.8 dB. When $L_{Aeq,8h}$ = 75 dBA, the calculated $NIPTS_{346}$ is 6.5 dB. It is worth noting that the K_3 curve and K_2 curve intersect around $L_{Aeq,8h}$ = 78 dBA. When the noise level is greater than 78 dBA, the $NIPTS_{346}$ difference between groups K_3 and K_2 becomes

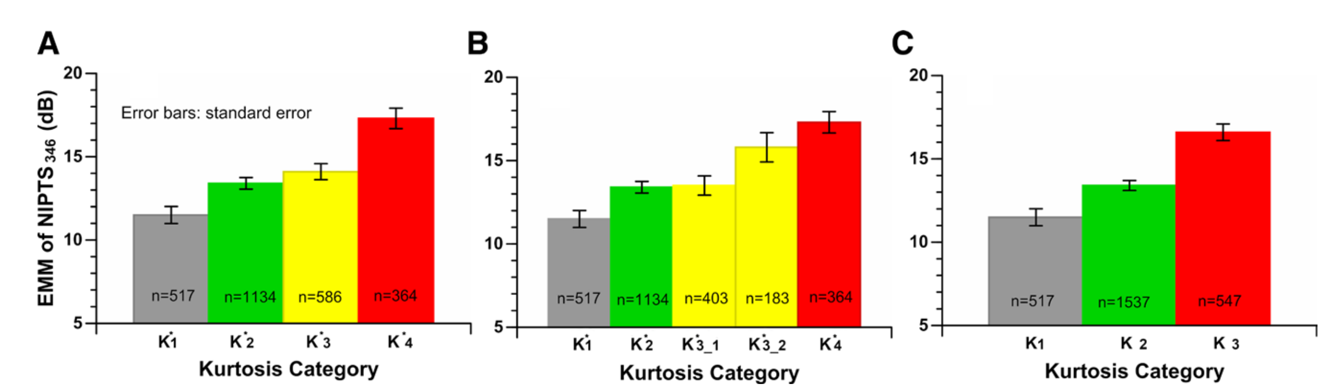

Fig. 4. The estimated marginal mean of $NIPTS_{346}$ at each kurtosis category. A, Four kurtosis categories (K_1^*, K_2^*, K_3^*, and K_4^*) in Zhang et al. (2021); (B) five kurtosis categories; and (C) three kurtosis categories (K_1, K_2, and K_3) used in the current study. Error bars: standard error. n: number of workers in the kurtosis category.

TABLE 5. The kurtosis distribution information of some work types in the manufacturing industry [n: the number of workers investigated in the kurtosis analysis in the corresponding work type; correction value = 6.5*$\log_{10}(\beta/3)$, where the β is the mean of the kurtosis values of all the workers in that work type]

Industry	Work Type	Kurtosis (β) Mean±SD (Min–Max)	Correction (dB)	Unadjusted $L_{Aeq.8h}$ (dBA) Mean±SD (Min–Max)	n
K_1 ($3 \le \beta_N \le 10$)					
Textile mill	Spinning	3.3 ± 2.1 (3.0–9.4)	0.3	98.7 ± 2.3 (93.8–102.0)	109
	Weaving	4.1 ± 3.0 (3.1–11.7)	0.9	92.4 ± 2.4 (85.9–95.6)	49
	Knitter	5.2 ± 2.2 (3.3–17.5)	1.6	97.5 ± 1.8 (93.3–104.9)	84
	Mechanist	8.6 ± 4.6 (4.0–17.8)	3.0	93.5 ± 5.0 (84.9–98.4)	14
Spandex	Winding	9.7 ± 4.4 (3.2–23.7)	3.3	95.8 ± 4.7 (82.3–104)	52
Papermill	Defibrinating	6.6 ± 2.8 (4.3–8.4)	2.2	87.1 ± 2.2 (84.5–90.4)	7
	Pulping	9.0 ± 3.8 (3.0–15.4)	3.1	89.0 ± 4.1 (82.2–96.9)	28
	Rewinder	8.6 ± 2.3 (3.5–12)	3.0	88.3 ± 2.5 (84.9–92.5)	11
K_2 ($10 < \beta_N \le 50$)					
Auto brake pad manufactory	Assemblyman	36.3 ± 16.1 (9.6–72.8)	7.0	85.6 ± 5.2 (71.7–96.7)	57
	Machining	32.6 ± 28.1 (8.6–141.9)	6.7	89.0 ± 5.2 (77.4–103.8)	100
Auto parts manufactory	Thread rolling	11.2 ± 4.9 (3.9–25.3)	3.7	89.5 ± 2.8 (82.5–94.6)	41
	Depositing	13.7 ± 7.1 (5.0–32.1)	4.3	88.8 ± 3.0 (83.0–97.7)	19
	Tapping	15.2 ± 7.0 (6.8–27.9)	4.6	90.1 ± 1.7 (86.5–92.9)	14
	Numerical control machine	15.5 ± 9.4 (7.8–32.0)	4.6	87.0 ± 5.5 (79.3–93.1)	6
	Spot welding	16.1 ± 5.0 (6.6–22.5)	4.7	90.2 ± 2.0 (87–93.5)	11
	Lathe worker	16.6 ± 13.7 (4.1–63.3)	4.8	85.9 ± 4.3 (72.8–92.4)	21
	Drawing wire	17.4 ± 8.4 (7.0–32.5)	5.0	88.9 ± 4.1 (82.9–98.0)	16
	Packing	21.2 ± 10.5 (6.4–43.2)	5.5	85.2 ± 4.7 (73.6–91.0)	33
	Sorting	22.2 ± 14.8 (4.2–81.3)	5.6	87.0 ± 3.7 (78.7–93.6)	38
Automotive fasteners	Electroplating	17.3 ± 12.7 (4.1–63.4)	4.9	89.9 ± 6.4 (76–103.8)	31
	Cold heading	25.2 ± 16.9 (4.7–79.7)	6.0	90.4 ± 5.2 (80.9–104.7)	60
	Polishing	25.7 ± 16 (4.8–54.8)	6.1	92.1 ± 6.4 (80.7–100.3)	10
	Heat treatment	27.3 ± 18.7 (6.5–78)	6.2	89.9 ± 4.1 (82.5–99.9)	31
	Automatic lathe work	29.6 ± 17 (6.3–67.6)	6.5	89.2 ± 4.8 (81.5–96.7)	16
Baby carriage manufactory	Punch	15.6 ± 5.4 (7.5–29.0)	4.6	93.9 ± 3.2 (87.6–98.6)	42
	Stamping	28.4 ± 18.4 (7.8–85.9)	6.3	91.7 ± 8.2 (73.5–105.4)	85
Commercial vehicle body factory	Craneman	24.0 ± 20.2 (3.5–88.7)	5.9	90.6 ± 6.0 (78.6–104.3)	25
	Spot welding	26.6 ± 21.6 (5–104.4)	6.2	89.8 ± 3.3 (83.7–97.8)	23
	Electric welder	40.0 ± 29.4 (3.4–187.1)	7.3	91.5 ± 7.4 (77.3–104.1)	79
Electrical appliance factory	Stretching	26.3 ± 9.7 (15.8–47.7)	6.1	87.6 ± 3.1 (82.9–95.6)	12
	Sanding	26.9 ± 20.1 (6.1–76.8)	6.2	87.1 ± 5.0 (75.8–94.6)	9
Electrical appliance factory	Forming	27.8 ± 12.6 (12.9–50.4)	6.3	79.8 ± 3.8 (75.3–88.0)	8
	Assemblyman	50.0 ± 27.7 (19.7–91.8)	7.9	76.4 ± 2.5 (73.0–80.1)	18
Final assembly plant for automobiles	Machining	19.7 ± 8.9 (8.1–34.6)	5.3	88.8 ± 4.7 (82.7–98.6)	9
	Assemblyman	28.0 ± 25.2 (3.4–196.2)	6.3	90.9 ± 5.0 (79.8–105.6)	221
Hardware factory	Sand blast	11.4 ± 2.9 (8.1–15.8)	3.8	90.1 ± 2.1 (87.5–93.5)	8
	Stamping	20.2 ± 11.0 (7.1–48.5)	5.4	87.5 ± 4.2 (76–93.5)	20
	Benchwork	33.2 ± 24.3 (10.0–92.4)	6.8	83.2 ± 5.3 (75–92.7)	11
Heavy truck engine factory	Casting	21.2 ± 16.1 (8–55.7)	5.5	89.7 ± 9.0 (81.9–113)	10
Hydroelectric	Drilling	21.3 ± 10.6 (7.2–39.1)	5.5	90.2 ± 5.5 (81.5–99.7)	15
	Cold operating	42.4 ± 18.9 (13.4–78.4)	7.5	95.6 ± 3.6 (90.3–100.3)	8
	Modeling	42.8 ± 18.1 (12.0–75.3)	7.5	88.9 ± 6.2 (73.5–94.6)	10
Iron and steel plant	Steel rolling	14.4 ± 9.1 (4.6–58.9)	4.4	90.5 ± 5.3 (76.9–96.7)	41
	Finishing	16.8 ± 8.2 (6.1–42.4)	4.9	88.4 ± 4.3 (74.2–99.8)	21
	Loading	22.4 ± 4.1 (13.3–25.1)	5.7	86.7 ± 2.9 (83.3–90.6)	8
Machinery	Grinding	26.2 ± 10.4 (16.1–58.7)	6.1	84.6 ± 6.4 (72.6–93.8)	13
	Metal processing	47.6 ± 19.6 (26.2–80.5)	7.8	82.2 ± 2.3 (79.0–85.4)	7
Machinery and electric	Assemblyman	37.8 ± 28.6 (7.8–240.7)	7.1	86.2 ± 3.2 (77.7–98.0)	147
K3 ($\beta_N > 50$)					
Electrical appliance	Wiring	53.7 ± 41.7 (16.2–156.6)	8.1	75.6 ± 2.3 (71.2–79.2)	10
Furniture manufactory	Frame nailing	81.7 ± 44.3 (24.9–158.5)	9.3	89.5 ± 5.4 (76.3–100.5)	51
	Woodworking	119.2 ± 71.6 (21.3–306.8)	10.4	88.5 ± 3.6 (81.9–95.4)	23
	Assemblyman	102.4 ± 69.6 (42.2–250)	10.0	89.2 ± 4.3 (83.9–96.9)	12
	Nail gunning	246.5 ± 172.2 (31.5–925.5)	12.4	89.0 ± 4.4 (76.7–98.8)	213
Grid structure	Assemblyman	103.0 ± 69.7 (34.3–315.6)	10.0	93.8 ± 3.5 (87.3–101)	26
Kitchen and bath manufacturing	Assemblyman	69.7 ± 62.9 (17.4–177.2)	8.9	81.6 ± 2.3 (77.9–85.0)	13

larger and larger. Especially when $L_{Aeq,8h} \geq 85$ dBA, the $NIPTS_{346}$ in group K_3 was significantly higher than that in groups K_2 and K_1. At the range between 85 and 95 dBA, the higher the noise level, the greater the difference in $NIPTS_{346}$. According to the equations of the three fitting curves, it can be found that when $L_{Aeq,8h}$ is greater than 100 dBA, the $NIPTS_{346}$ difference between K_3 group and K_1/K_2 group tends to be stable (about 4 dB).

It is worth mentioning that, as we pointed out in our previous study, kurtosis is an adjunct metric to energy in the evaluation of NIHL (Qiu et al. 2006); that is to say, energy is the primary metric. If the noise energy does not reach a certain "threshold," then kurtosis will not have much effect on NIHL. As can be seen from the previous discussion, if $L_{Aeq,8h}$ is below 70 dBA, neither continuous noise nor complex noise can produce significant $NIPTS_{346}$. Therefore, we can infer that the noise level of $L_{Aeq,8h} = 70$ dBA is the "threshold" for the effect of kurtosis. When $L_{Aeq,8h} < 70$ dBA, the value of kurtosis does not have an impact on NIHL evaluation.

Animal Versus Human Adjustment for Kurtosis

Animal and epidemiological studies have shown that the temporal structure of noise (kurtosis) plays a vital role in NIHL evaluation (Lei et al. 1994; Qiu et al. 2006; Hamernik et al. 2007; Zhao et al. 2010). Based on these animal and epidemiological studies' findings, Goley (2011) proposed a scheme to correct the measured noise level ($L_{Aeq,8h}$) using kurtosis and derived the adjustment coefficient of $\lambda = 4.02$ from an analysis of chinchilla noise-exposure data. However, it is essential to note that the NIHL results observed in chinchillas are different from those observed in humans, where chinchillas are more susceptible to developing hearing loss following noise exposures. Therefore, the adjustment coefficient (λ) obtained from the chinchilla noise data does not necessarily apply to humans. As a comparison, we directly applied $\lambda = 4.02$ to workers' data, and the results are shown in Figure 3. It can be seen that, although using this coefficient can reduce the underestimation of NIHL caused by complex noise to some extent, for example, the K_2 group's underestimation was reduced from the original average of 6.35 dB to 2.8 dB, the underestimation degree of K_3 group was reduced from the original average of 10.24 dB to 4.5 dB, but the degree of hearing damage caused by noise with high kurtosis value was still vastly underestimated.

Since human hearing is not as sensitive as that of chinchilla, it can be seen from adjustment formula (7) that to suffer a fixed NIHL, the adjustment coefficient of the human model should be larger than that of chinchilla. In other words, humans need to receive more noise energy than chinchillas do to suffer a comparable NIHL. Using data collected from the industrial and non-noise population in China and the ISO 1999 prediction formula for NIPTS, we derived an optimum adjustment coefficient ($\lambda = 6.5$) that could be applied practically to protect the hearing of workers by using Goley's correction formula. As can be seen from Figure 3, after the adjustment of $L_{Aeq,8h}$ by kurtosis, (1) for workers exposed to steady state noise ($\beta \leq 10$, group K_1), the underestimation of $NIPTS_{346}$ by ISO 1999 decreased significantly from 3.72 dB to 1.23 dB; (2) for workers exposed to complex noise with medium kurtosis ($10 < \beta_N \leq 50$, group K_2), the underestimation of $NIPTS_{346}$ by ISO 1999 decreased significantly from 6.35 dB to 0.08 dB. It is clear that after kurtosis adjustment, ISO 1999 was able to accurately predict high-frequency hearing loss of workers in the K_2 group. Considering that most occupational noises belong to this type of non-Gaussian complex noise (59.1% of the total number of workers exposed to this type of noise in our collected data), the adjustment of kurtosis to L_{Aeq} is of great significance for the correction of the ISO 1999 prediction formula. (3) For workers exposed to complex noise with high kurtosis ($\beta_N > 50$, group K_3), the underestimation of $NIPTS_{346}$ by ISO 1999 decreased significantly from 10.24 dB to −0.96 dB. This result shows that kurtosis has a significant adjustment on L_{Aeq} with greater impulsive content ($\beta > 50$), although the overall adjustment effect is slightly over-adjusted (about 1 dB overestimation for $NIPTS_{346}$). It is worth pointing out that in the Introduction of the ISO 1999:2013 document, it is particularly emphasized that: "Throughout this International Standard, the term NIPTS is applied to changes in the noise-induced permanent threshold shift of statistical distributions of groups of people; it is not to be applied to individuals." Similarly, the evaluation of the kurtosis adjustment effect on NIPTS in this study is also based on groups of people rather than individuals.

The reason for choosing 3 to 6 kHz for investigating NIPTS in this study is that hearing loss initially occurs mainly in this frequency range under stable noise exposure conditions. Therefore, from the perspective of hearing protection, we should study the dose-response relationship in the frequency band where it is the most sensitive to NIHL and find the optimal kurtosis adjustment algorithm to evaluate NIHL better to prevent hearing loss to the greatest extent. However, the NIPTS produced by complex noise may have different trajectories in frequency from continuous noise. In addition, NIPTS of other test frequencies (e.g., 1, 2, and 8 kHz) should also be studied, as these bands are important for speech recognition and understanding. The above topics are beyond the scope of this study and will be of great significance as future research work.

ISO 1999 Implications and Kurtosis Application

In the formulation and revision of ISO1999 over the years, researchers have taken into account the different effects of impulsive noise and steady-state noise on hearing. Therefore, in the ISO1999:1971, it was pointed out that a correction of 10-dB should be added on the basis of the measured L_{Aeq} for impulsive noise. In ISO 1999:1990, the correction value was changed to 5 dB. Since no specific method is given to distinguish steady-state noise from impulsive noise, such correction is arbitrary. Using the kurtosis correction formula of Equation 7 with the adjustment coefficient $\lambda = 6.5$, one may find that a correction of 5 dB corresponds to a moderately impulsive complex noise with a moderate kurtosis value (e.g., $\beta = \sim 20$), and a correction of 10-dB corresponds to a highly impulsive complex noise with a high kurtosis value ($\beta > 75$). Therefore, the kurtosis correction formula can be explicitly used to evaluate the hearing loss of complex noise with different impulsive components, which can help government agencies develop better noise standards and hearing protection programs. Once there is an international standard to address what should be measured, how it is measured, and how it can be applied, adding a kurtosis metric is a straightforward modification to the software included in a sound level meter or dosimeter.

Meanwhile, we should pay attention to the application scope of kurtosis. Since the kurtosis metric is an adjunct to energy in the evaluation of trauma from complex noise exposure, the validity of kurtosis depends on the noise exposure level. If the equivalent energy level of the noise exposure is low (e.g., less than 70 dB), it will not contribute to hearing loss no matter how high the value of kurtosis is. On the other hand, if the peak level of an impulse noise exceeds 140 dB SPL, the mechanisms of hearing damage include both mechanical and strains. The use of kurtosis would be questionable because there are no data about its effectiveness in this area. In order to greatly reduce the dose-response bias due to the wearing of hearing protection devices, the noise exposure range of this study was 70 to 95 dBA. In addition, due to the insufficient sample size at 70 to 78 dBA (especially for K_1 and K_3 groups), more data are needed to explore the relationship between kurtosis and energy interaction in this region.

Consideration of Race/Ethnicity Influences on the Outcomes

The database in this study was collected from a population of Chinese workers. There can be concern about the extent to which the results are applicable to populations of other non-Chinese ethnicities. Evans and Ming (1982) investigated 300 subjects exposed to industrial noise and 200 non-exposed (control) subjects in Hong Kong. Their results indicated that there was no evidence for ethnic differences between Western groups and Cantonese Chinese either for general hearing levels or for response to prolonged exposure to industrial noise. Furthermore, in the Chinese national standard document GZB 49-2014 (2014), the table showing the statistical distribution of median hearing thresholds as a function of age for an otologically screened population is the same as Annex A in ISO 1999 (1990). Also, Korea recently conducted the Korean National Health and Nutrition Examination Survey (KNHANES) 2010 to 2012 (Park et al. 2016). Median hearing thresholds between the KNHANES 2010 to 2012 and the USA National Health and Nutrition Examination Survey 1999 to 2004 were compared across age groups and gender. No difference in hearing thresholds between the USA population and the Korean population was found. From these studies, it was found that the hearing threshold of Chinese people was not significantly different from that of Americans or Westerners. It follows that the outcomes of this study can be applied to different ethnic groups.

CONCLUSIONS

In this study, the combined effects of noise exposure level and kurtosis on NIHL were analyzed by using data collected from 2601 Chinese workers exposed to various industrial noises in comparison to non-noise exposed workers (n = 1297). The Goley model was re-investigated, and the adjustment coefficient, that is, λ, was recalculated. The following conclusions can be addressed:

1. Because non-Gaussian complex noise is present in a wide range of industries, the temporal characteristics of noise (i.e., kurtosis) must be considered when evaluating occupational NIHL.
2. For non-Gaussian complex noise (β > 10), NIHL may occur when L_{Aeq} is greater than 70 dBA, and NIHL is pronounced when L_{Aeq} is larger than 80 dBA. Therefore, any singular occupational REL will be insufficient to protect the hearing of workers unless kurtosis adjustment is applied.
3. A kurtosis-adjusted $L_{Aeq,8h}$ with an adjustment coefficient of 6.5 allows a more accurate prediction of high-frequency NIHL in the region of 70 dBA ≤ L_{Aeq} ≤ 95 dBA, which is very important for the hearing protection of workers exposed to various complex noises.

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M. B. Z. designed and performed the investigation, analyzed data, and wrote part of the original draft; X. J. G. conducted the field investigation, subject selection and interview, data evaluation, and quality control; W. J. M. and C. A. K. validated the project and methodology, reviewed and edited the article; X. S. was responsible for project administration, validate the results of data analysis, and article review; W. J. H. and J. S. L. conducted project supervision and provided the discussion; W. G. conducted the field investigation and quality control; W. Q. designed and supervised the project, analyzed data, wrote and edited the article. All authors discussed the results and implications and commented on the manuscript at all stages.

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