



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 ( $\beta$ ), 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 ( $85 \leq L_{Aeq,8h} < 88$ ,  $88 \leq L_{Aeq,8h} < 91$ ,  $91 \leq L_{Aeq,8h} < 94$ , and  $94 \leq L_{Aeq,8h} \leq 100$  dBA), two exposure durations ( $D \leq 10$  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 ( $\beta$ ). 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  $L_{Aeq,T_e}$  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:

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

where  $x_i$  is the  $i$ th 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**

Industry Category	Main Productions	Number of Factories	Typical Noise Sources	Participants					
				Male (n)	Female (n)	Age (year)*	Duration (year)*	L <sub>Aeq,8h</sub> (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:

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

where L<sub>Aeq,8h</sub> is the noise exposure level normalized to a nominal 8hr working day; t is noise exposure duration in years, t<sub>0</sub> = 1; L<sub>0</sub> 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 2–6kHz because noise-induced hearing loss occurs predominantly in this range. The NIPTS predictions for each participant at test frequencies (2, 3, 4, and 6kHz) 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<sub>1</sub>: 85 ≤ L<sub>Aeq,8h</sub> < 88 dBA;
- (2) L<sub>2</sub>: 88 ≤ L<sub>Aeq,8h</sub> < 91dBA;
- (3) L<sub>3</sub>: 91 ≤ L<sub>Aeq,8h</sub> < 94 dBA;
- (4) L<sub>4</sub>: 94 ≤ L<sub>Aeq,8h</sub> ≤100 dBA.

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

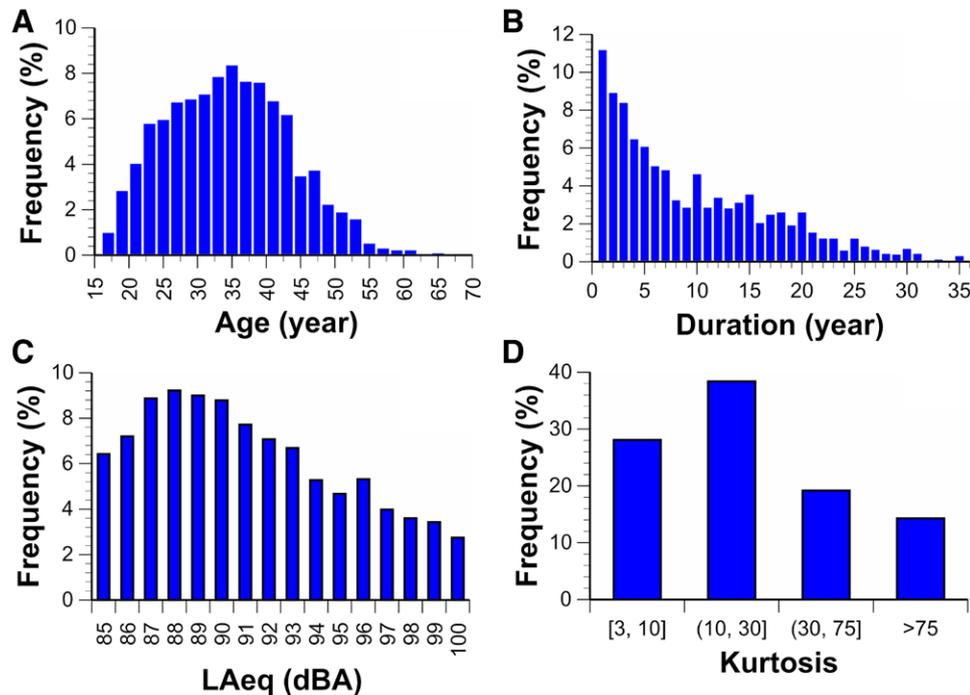


Fig. 1. Distributions of (A) age; (B) exposure duration; (C) A-weighted equivalent sound pressure levels ( $L_{Aeq,8h}$ ); and (D) kurtosis value of the 2,333 noise-exposed workers.

(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  $\beta = 3, 25, 50, \text{ or } 100$  at 97 dB SPL. The results showed that cochlear sensory cell loss increased with increasing  $\beta(t)$  (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 [ $10 < \text{mean } \beta(t) \leq 30$ ];
- (c)  $K_3$ : Medium kurtosis group [ $30 < \text{mean } \beta(t) \leq 75$ ];
- (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 <sub>Aeq</sub> *	L <sub>1</sub>	12.6	0.6	11.5 to 13.7
	L <sub>2</sub>	11.9	0.5	10.9 to 12.8
	L <sub>3</sub>	9.8	0.5	8.8 to 10.8
	L <sub>4</sub>	4.4	0.5	3.4 to 5.5
Duration†	D <sub>1</sub>	11.4	0.3	10.8 to 12.0
	D <sub>2</sub>	8.0	0.4	7.1 to 8.8
Duration × L <sub>Aeq</sub>	D <sub>1</sub> × L <sub>1</sub>	13.1	0.5	12.0 to 14.1
	D <sub>1</sub> × L <sub>2</sub>	13.7	0.5	12.8 to 14.7
	D <sub>1</sub> × L <sub>3</sub>	10.7	0.6	9.6 to 11.8
	D <sub>1</sub> × L <sub>4</sub>	8.0	0.7	6.7 to 9.3
	D <sub>2</sub> × L <sub>1</sub>	12.1	1.1	9.9 to 14.3
	D <sub>2</sub> × L <sub>2</sub>	10.0	0.9	8.2 to 11.8
	D <sub>2</sub> × L <sub>3</sub>	8.8	0.9	7.1 to 10.6
	D <sub>2</sub> × L <sub>4</sub>	0.9	0.9	−0.9 to 2.8
Kurtosis‡	K <sub>1</sub>	7.5	0.4	6.6 to 8.3
	K <sub>2</sub>	8.7	0.4	8.0 to 9.4
	K <sub>3</sub>	8.9	0.5	7.8 to 9.8
	K <sub>4</sub>	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<sub>1</sub>–L<sub>2</sub> pair; 0.001\*\* for L<sub>1</sub>–L<sub>3</sub> pair; <0.001\*\* for L<sub>1</sub>–L<sub>4</sub> pair; 0.017\*\* for L<sub>2</sub>–L<sub>3</sub> pair; <0.001\*\* for L<sub>2</sub>–L<sub>4</sub> pair; <0.001\*\* for L<sub>3</sub>–L<sub>4</sub> pair.  
 †p value for difference between D<sub>1</sub> and D<sub>2</sub> is <0.001\*\*.  
 ‡p values for difference between kurtosis group pair are as follows: 0.162 for K<sub>1</sub>–K<sub>2</sub> pair; 0.259 for K<sub>1</sub>–K<sub>3</sub> pair; <0.001\*\* for K<sub>1</sub>–K<sub>4</sub> pair; 1.0 for K<sub>2</sub>–K<sub>3</sub> pair; <0.001\*\* for K<sub>2</sub>–K<sub>4</sub> pair; <0.001\*\* for K<sub>3</sub>–K<sub>4</sub> 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* ≤ 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 ≤ L<sub>Aeq,8h</sub> < 88 dBA (group L<sub>1</sub>), 88 ≤ L<sub>Aeq,8h</sub> < 91 dBA (group L<sub>2</sub>), 91 ≤ L<sub>Aeq,8h</sub> < 94 dBA (group L<sub>3</sub>), and 94 ≤ L<sub>Aeq,8h</sub> ≤ 100 dBA (group L<sub>4</sub>), 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<sub>4</sub> level group than in the other three level groups (*p* < 0.001 for all three comparisons). The degree of NIPTS underestimation in the L<sub>3</sub> level group was significantly less than in the L<sub>1</sub> and L<sub>2</sub> groups (*p* = 0.001 and 0.017, respectively). There was no significant difference between L<sub>1</sub> and L<sub>2</sub> 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* ≤ 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<sub>1</sub>); by 8.7 dB for the low kurtosis group (K<sub>2</sub>); by 8.9 dB for the medium kurtosis group (K<sub>3</sub>); and by 13.6 dB for the high kurtosis group (K<sub>4</sub>). The extent of NIPTS underestimation increased with the increase of kurtosis value. The underestimated NIPTS by the ISO 1999 model for the K<sub>4</sub> 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<sub>1</sub> duration group (N = 1,340) and the D<sub>2</sub> 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<sub>1</sub> 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<sub>2</sub> group. The estimated marginal means for the D<sub>1</sub> and D<sub>2</sub> 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* ≤ 10-year group (Figure 2A), the ISO 1999 model underestimated NIPTS by 6.1 to 11.5 dB in participants exposed to Gaussian (K<sub>1</sub>) noise and 7.6 to 17.1 dB in participants exposed to non-Gaussian (K<sub>2</sub>, K<sub>3</sub>, and K<sub>4</sub>) noise at all four noise levels (L<sub>1</sub> to L<sub>4</sub>). 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  $D \leq 10$  years and  $D > 10$  years

Duration	Effect	Group	Estimated Mean	Standard Error	95% CI
$D \leq 10$ 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	$L_{Aeq}^\ddagger$	$L_1$	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,  $D \leq 10$  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.

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 decreased 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

**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.

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  $D \leq 10$  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 was 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  $D \leq 10$  years and  $D > 10$  years**

Duration	Effect	Group	Estimated	Standard	95% CI
			Mean	Error	
$D \leq 10$ 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	$L_{Aeq}^\ddagger$	$L_1$	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,  $D \leq 10$  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).

**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 &

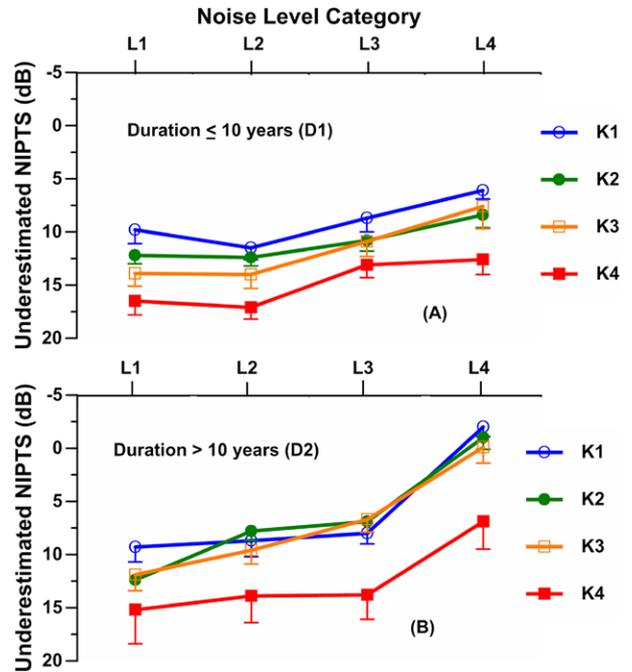


Fig. 2. The estimated marginal means (EMM) of underestimated NIPTS by ISO 1999 model at each kurtosis value across test frequencies for four noise level bins in two different exposure durations. (A) The EMM of NIPTS underestimation at each kurtosis value for our noise level bins in duration  $D \leq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

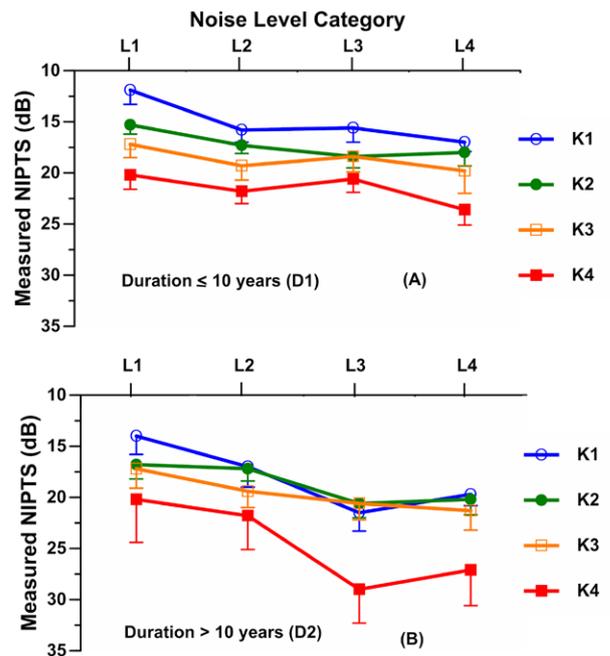


Fig. 3. The estimated marginal means (EMM) of the actual measured NIPTS at each kurtosis value across test frequencies for four noise level bins in two different exposure durations. (A) The EMM of the actual measured NIPTS at each kurtosis value for our noise level bins in duration  $D \leq 10$  years.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

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 suggest 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.

## ACKNOWLEDGMENTS

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

The authors wish to thank those who agreed to participate in the study for their time, interest, and cooperation. Dr. Roger Hamernik from SUNY Plattsburgh, Drs. Robert Park and Edward Zechmann from the National Institute for Occupational Safety and Health provided helpful critiques of the manuscript. This work was sponsored by Grant 200-2015-M-63857, 200-2016-M-91922 from the National Institute for Occupational Safety and Health, USA; Grant N00014-17-1-2198 from Office of Naval Research, USA; Zhejiang province key research and development project (2015C03039), China; Zhejiang Provincial Program for the Cultivation of High-level Innovative Health Talents, China; and Health Commission of Zhejiang Province (2019KY057), China. Grant No. 81771936 from National Natural Science Foundation, China. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

The authors declare that they have no actual or potential competing financial interests.

Address for correspondence: Wei Qiu, Auditory Research Laboratory, State University of New York at Plattsburgh, 101 Broad St, Plattsburgh, NY 12901, USA. E-mail: qiuw@plattsburgh.edu. Hua Zou, Zhejiang Provincial Center for Disease Control and Prevention, Hangzhou 310051, Zhejiang, P.R. China. E-mail: hzou@cdc.zj.cn

Received October 4, 2019; accepted July 15, 2020.

## REFERENCES

Ahroon, W. A., Hamernik, R. P., & Davis, R. I. (1993). Complex noise exposures: An energy analysis. *J Acoust Soc Am*, *93*, 997–1006.

American National Standards Institute. (2003). *Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms*. ANSI S3.1-1999. New York.

Burns, W., and Robinson, D. W. (1970). *Hearing and Noise in Industry*. Her Majesty's Stationery Office.

Canlon, B., Borg, E., & Flock, A. (1988). Protection against noise trauma by pre-exposure to a low-level acoustic stimulus. *Hearing Res*, *34*, 197–200.

Clark, W. W. (1991). Recent studies of temporary threshold shift (TTS) and permanent threshold shift (PTS) in animals. *J Acoust Soc Am*, *90*, 155–163.

Davis, R. I., Qiu, W., Heyer, N. J., Zhao, Y., Yang, Q., Li, N., Tao, L., Zhu, L., Zeng, L., Yao, D. (2012). The use of the kurtosis metric in the evaluation of occupational hearing loss in workers in China: implications for hearing risk assessment. *Noise Health*, *14*, 330–342.

Dobie, R. A. (2001). *Medical-Legal Evaluation of Hearing Loss* (2nd ed.). Singular.

Dunn, D. E., Davis, R. R., Merry, C. J., & Franks, J. R. (1991). Hearing-loss in the chinchilla from impact and continuous noise exposure. *J Acoust Soc Am*, *90*, 1979–1985.

Earshen, J. J. (1980). Noise dosimeters: On measurement reliability and instrument accuracy. *J Acoust Soc Am*, *68*, S21.

Earshen, J. J. (1994). On comparing noise metrics applied to hearing conservation. *J Acoust Soc Am*, *96*, 3272–3272.

Erdreich, J. (1986). A distribution based definition of impulse noise. *J Acoust Soc Am*, *79*, 990–998.

Flamme, G. A., Deiters, K., & Needham, T. (2011). Distributions of pure-tone hearing threshold levels among adolescents and adults in the United States by gender, ethnicity, and age: Results from the US National Health and Nutrition Examination Survey. *Int J Audiol*, *50*, S11–S20.

Flamme, G. A., Deiters, K. K., Stephenson, M. R., Themann, C. L., Murphy, W. J., Byrne, D. C., Goldfarb, D. G., Zeig-Owens, R., Hall, C., Prezant, D.J., & Cone, J.E. (2020). Population-based age adjustment tables for use in occupational hearing conservation programs. *Int J Audiol*, *59*, S20–S30.

Hamernik, R. P., & Qiu, W. (2001). Energy-independent factors influencing noise-induced hearing loss in the chinchilla model. *J Acoust Soc Am*, *110*, 3163–3168.

Hamernik, R. P., Qiu, W., & Davis, B. (2003). The effects of the amplitude distribution of equal energy exposures on noise-induced hearing loss: The kurtosis metric. *J Acoust Soc Am*, *114*, 386–395.

Hoffman, H. J., Dobie, R. A., Ko, C. W., Themann, C. L., Murphy, W. J. (2010). Americans hear as well or better today compared with 40 years ago: hearing threshold levels in the unscreened adult population of the United States, 1959-1962 and 1999-2004. *Ear Hear*, *31*, 725–734.

ISO 1999 (2013). *Acoustics—Estimation of Noise-Induced Hearing Loss*. International Organization for Standardization.

Johansson, M., & Arlinger, S. (2004). Reference data for evaluation of occupationally noise-induced hearing loss. *Noise Health*, *6*, 35–41.

Jun, H. J., Hwang, S. Y., Lee, S. H., Lee, J. E., Song, J. J., Chae, S. (2015). The prevalence of hearing loss in South Korea: data from a population-based study. *Laryngoscope*, *125*, 690–694.

Lataye, R., & Campo, P. (1996). Applicability of the Leq as a damage-risk criterion: An animal experiment. *J Acoust Soc Am*, *99*, 1621–1632.

Lei, S. F., Ahroon, W. A., & Hamernik, R. P. (1994). The application of frequency and time-domain kurtosis to the assessment of hazardous noise exposures. *J Acoust Soc Am*, *96*, 1435–1444.

Lempert, B. (2019). ISO estimates of noise-induced hearing impairment. *J Acoust Soc Am*, *145*, 3640.

Lutman, M. E., & Davis, A. C. (1996). Distributions of hearing threshold levels in populations exposed to noise. In A. Axelsson, H. Borchgrevink, R. P. Hamernik, P. Hellstrom, D. Henderson, & R. Salvi (Eds.), *Scientific Bases of Noise-Induced Hearing Loss* (pp. 378–396). Thieme, New York.

Mills, J. H., Lee, F., Dubno, J. R., & Boettcher, F.A. (1996). Interactions between age-related and noise-induced hearing loss: In A. Axelsson, H. Borchgrevink, R. P. Hamernik, P. Hellstrom, D. Henderson, & R. Salvi (Eds.), *Scientific Bases of Noise-Induced Hearing Loss* (pp. 193–212). Thieme.

NIOSH. (1998). *Criteria for a Recommended Standard: Occupational Noise Exposure-Revised Criteria*. U.S. Department of Health, Education, and Welfare. National Institute for Occupational Safety and Health. Publication no. 98-126.

Park, Y. H., Shin S. H., Byun, S. W., & Kim J. Y. (2016). Age- and gender-related mean hearing threshold in a highly-screened population: The Korean National Health and Nutrition Examination Survey 2010–2012. *PLoS One*, *11*, e0150783.

Passchier-Vermeer, W. (1977). Hearing levels of non-noise exposed subjects and of subjects exposed to constant noise during working hours. Report No. B-367. Research Institute for Environmental Hygiene.

Qiu, W., Hamernik, R. P., & Davis, B. (2006). The kurtosis metric as an adjunct to energy in the prediction of trauma from continuous, non-Gaussian noise exposures. *J Acoust Soc Am*, *120*, 3901–3906.

- Qiu, W., Davis, B., & Hamernik, R. P. (2007). Hearing loss from interrupted, intermittent, and time varying Gaussian noise, exposures: The applicability of the equal energy hypothesis. *J Acoust Soc Am*, *121*, 1613–1620.
- Qiu, W., Hamernik, R. P., & Davis, R. I. (2013). The value of a kurtosis metric in estimating the hazard to hearing of complex industrial noise exposures. *J Acoust Soc Am*, *133*, 2856–2866.
- Rodríguez, V. A., Roldán, F. A., García, B. J. R., & Ramírez, C. R. (2015). Hearing threshold levels for an otologically screened population in Spain. *Int J Audiol*, *54*, 499–506.
- Sulkowski, W. J., Kowalska, S., & Lipowczan, A. (1983). Hearing loss in weavers and drop-forge hammermen: Comparative study on the effects of steady-state and impulse noise. In: Proceedings of the 4th International Congress—Noise as a Public Health Problem, ed. G. Rossi, Turin, Italy (pp. 171–184).
- Tambs, K., Hoffman, H. J., Borchgrevink, H. M., Holmen, J., & Engdahl, B. (2006). Hearing loss induced by occupational and impulse noise: Results on threshold shifts by frequencies, age and gender from the Nord-Trøndelag Hearing Loss Study. *Int J Audiol*, *45*, 309–317.
- Taylor, W., Lempert, B., Pelmeur, P., Hemstock, I., & Kershaw, J. (1984). Noise levels and hearing thresholds in the drop forging industry. *J Acoust Soc Am*, *76*, 807–819.
- Thiery, L., & Meyer-Bisch, C. (1988). Hearing loss due to partly impulsive industrial noise exposure at levels between 87 and 90 dB. *J Acoust Soc Am*, *84*, 651–659.
- Ward, W. D. (1991). The role of intermittence in PTS. *J Acoust Soc Am*, *90*, 164–169.
- Xie, H. W., Qiu, W., Heyer, N. J., Zhang, M. B., Zhang, P., Zhao, Y. M., Hamernik, R. P. (2016). The use of the kurtosis-adjusted cumulative noise exposure metric in evaluating the hearing loss risk for complex noise. *Ear Hear*, *37*, 312–323.
- Zhao, Y. M., Qiu, W., Zeng, L., Chen, S. S., Cheng, X. R., Davis, R. I., & Hamernik, R. P. (2010). Application of the kurtosis statistic to the evaluation of the risk of hearing loss in workers exposed to high-level complex noise". *Ear Hear*, *31*, 527–532.