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RESEARCH ARTICLE

A Quantitative Analysis of Kurtosis Impact on Occupational Complex Noise-Induced Hearing Loss

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ABSTRACT

Background: Workers in industry settings are often exposed to complex noise, which poses a greater risk to hearing loss than continuous noise at equivalent energy levels. Previous studies have identified kurtosis as an essential metric for evaluating complex noise-induced hearing loss (NIHL). This study aimed to characterize the distribution of workers exposed to complex noise, examine the associations between kurtosis and changes in hearing thresholds at various frequencies, and explore kurtosis's role in estimating NIHL and its integration into occupational hearing loss prevention programs.

Methods: The study quantitatively analyzed data from 2400 workers exposed to industrial complex noise and 1520 non-noise-exposed workers in China. Both arithmetic and geometric average kurtosis were used to characterize the work-shift noise records. Linear regression models assessed noise-induced permanent threshold shift (NIPTS) across different frequency ranges.

Results: For workers exposed to average noise levels between 80 and 92 dBA, increased kurtosis levels correlated with worsening NIPTS across frequencies from 0.5 to 8 kHz. However, the impact of kurtosis at lower noise exposure levels (70–79 dBA) remains uncertain.

Conclusions: Kurtosis is crucial for predicting hearing loss among workers exposed to complex noise at average levels of 85 and 90 dBA. The findings have potential implications for occupational safety and health, particularly for the recruitment of workers into hearing loss prevention programs. Further risk assessment analysis could use the noise kurtosis metric to examine the excess risk of NIHL associated with complex noise exposure.

1 | Introduction

Noise is a widespread occupational hazard around the world. The US National Institute for Occupational Safety and Health (NIOSH) estimates that 22 million US workers are exposed to hazardous noise levels at work each year [1]. In industrial settings, various equipment such as compressors, fans, and electric motors can generate continuous noise that typically varies by no more than (±) 3 dB [2]. However, when these types of equipment operate through a series of tasks over a work shift, they often generate sound levels that fluctuate more than 3 dB, resulting in a noise environment that is not uniformly distributed [2]. On the other hand, certain industrial activities involving solid collision between objects, such as hammering, dropping objects, or stamping, generate impact noise. Therefore in a typical industrial environment where multiple tasks and activities occur simultaneously, workers are exposed to complex noise. Complex noise refers to noise that is intermittent and/or contains both impulsive and continuous noise components.

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Complex noise exhibits various characteristics, such as irregular sound level, spectral content, intermittency, and impulsiveness. However, accurately measuring many of these characteristics remains challenging [3]. Consequently, when establishing current damage-risk criteria for occupational noise exposure, NIOSH relied on studies primarily focused on continuous noise levels [4, 5]. This equal energy principle, which assumes that all noise exposure with the same energy content is equally hazardous, does not account for the temporal features of noise exposure. Over the past several decades, findings from numerous studies investigating the temporal nature of noise in both animals and humans have reported that complex noise is more hazardous to hearing than continuous noise at equivalent energy levels [6–8]. They suggest that the effect on hearing is not solely related to the average noise level but also to the intermittent higher levels present in complex noise. To better evaluate complex noise, one approach is to use the kurtosis statistic [9]. Kurtosis can describe whether noise is complex and indicate the degree of impulsiveness or transient louder noise present. Continuous noise resulting from a Normal or Gaussian distribution has a kurtosis value of 3, while complex noise has a kurtosis value greater than 3.

Kurtosis has been investigated thoroughly in animal models during the last 30 years. Research conducted by Hamernik et al. from the State University of New York (SUNY) at Plattsburgh using an animal (chinchilla) model suggested that considering the kurtosis of amplitude distribution is necessary when applying the equal energy hypothesis [9, 10]. Later, Goley et al. analyzed noise exposure data for 273 chinchillas of 23 groups provided by SUNY Plattsburgh. The study involved data from chinchillas exposed to noise levels ranging from 90 to 100 A-weighted decibels (dBA) with corresponding kurtosis values ranging from 3.0 to 118 [11]. They reported a kurtosis adjustment factor λ of 4.02 in the animal model for A-weighted sound pressure level normalized to an 8-h working day ($L_{Aeq,8h}$) using the Formula 1 [11]. The kurtosis-adjusted level is

$$L'_{Aeq,8h} = L_{Aeq,8h} + \lambda \log_{10} \frac{\beta_N}{3}, \quad (1)$$

where $L'_{Aeq,8h}$ is the kurtosis-adjusted $L_{Aeq,8h}$, λ is the kurtosis adjustment coefficient, and β_N is the noise kurtosis value, a statistical measure of the amplitude "peakedness" of a noise waveform, with the impulsive components of complex noise as the outliers relative to a Gaussian noise [12].

These findings from animal models emphasize the consideration of not only average noise exposure levels but also noise kurtosis value when assessing the risk of complex occupational noise environments on hearing health. However, several important questions are raised: (1) does this finding apply to occupational noise exposure, (2) is the risk of hearing loss in humans moderated by different levels of kurtosis in addition to the noise exposure, (3) how kurtosis interacts with the equal energy principle, and (4) how to validate the effects of kurtosis on predicting occupational NIHL.

To find the answers, Qiu and his colleagues from SUNY Plattsburgh have focused on collecting data from industrial settings since 2008 and have published a series of articles. By collaborating with Peking University, they analyzed noise exposure data from one textile plant with Gaussian noise exposure (a mean kurtosis value of 3.3, $n = 32$) and data from one metal fabrication facility with non-Gaussian type containing high levels of impact noise (a mean kurtosis value of 40, $n = 195$). They concluded that the Kurtosis metric may be a reasonable candidate for use in modifying noise exposure level calculations in different noise environments [13]. Later, Tian et al. suggested a window length of 60 s for calculating kurtosis from the noise waveform after comparing 14 different window durations ((10 s, 40 s, 60 s, 2 min, 3.5 min, 4 min, 4.5 min, 5 min, 7.5 min, 10 min, 20 min, 30 min, 1 h, and full-shift) [14]. The published articles by Xie et al. ($n = 341$) [15], Zhang et al. ($n = 3102$ and 2333, respectively) [16, 17], and Xin et al. ($n = 1404$) [18] have used the arithmetic average of kurtosis to adjust noise levels. They also proposed using geometric mean kurtosis when calculating the kurtosis-adjusted noise level, as kurtosis is primarily distributed in a log-normal manner [14]. Other published articles by Xie et al. [15], Zhang et al. [16, 17], and Xin et al. [18] have used the arithmetic average of kurtosis to adjust noise levels. These studies also suggested that the kurtosis-adjusted cumulative noise exposure metric (K-CNE) – may be a reasonable candidate for assessing the risk of NIHL across various noise environments [15, 18]. The K-CNE metric was different from the Goley et al. proposed previously [11]

Furthermore, two articles estimated kurtosis coefficients to adjust $L_{Aeq,8h}$. In the first article by Gao et al. [19], data were analyzed from 2466 workers exposed to noise ranging from 70 to 95 dBA in six industries in China. The workers were classified into three subgroups based on the average kurtosis value (β) over a full shift: K1 ($\beta_N \leq 10$, steady noise), K2 ($10 \leq \beta_N \leq 50$, non-steady noise), and K3 ($\beta_N > 50$, non-steady noise). Measured hearing threshold levels (HLTs) at each frequency were adjusted by subtracting the median age- and sex-specific HTLs from a standard noise-exposed population described in the International Organization for Standardization (ISO) 1999:2013 [20]. The noise-induced permanent threshold shifts at 3, 4, and 6 kHz ($NIPTS_{346}$) were then calculated. Using a regression model, the kurtosis adjustment coefficient, $\lambda = 5.43$, was determined [19]. In the second article by Zhang et al. [21], the field data from the first article were expanded to a total of 4916 subjects. Among them, 2601 noise-exposed workers (ranging from 70 to 95 dBA) and 1297 non-noise-exposed participants (noise exposure below 70 dBA) were included. Kurtosis values were classified into three similar groups as K1 ($3 \leq \beta_N \leq 10$), K2 ($11 \leq \beta_N \leq 50$), and K3 ($\beta_N > 50$) based on the mean noise kurtosis over a full shift. However, measured hearing threshold levels of the better ear of the noise-exposed workers at each frequency were adjusted by subtracting normal median hearing threshold levels from an age- and sex-matched control population. $NIPTS_{346}$ was calculated with A-weighted equivalent continuous sound pressure level for an 8-h period ($L_{Aeq,8h}$) and noise kurtosis values fed into a regression model. The authors reported that the kurtosis adjustment coefficient λ was 6.5. In addition, they inferred that an $L_{Aeq,8h}$ noise level of 70 dBA is considered the "threshold" for the hearing loss effect of kurtosis [21]. A recent article ($n = 4276$) reported that using geometric mean of kurtosis or segmented adjustment approach could more accurately evaluate noise-induced hearing loss (NIHL) than by arithmetic averaging [22].

Recently, field measurements have been collected in the United States. Kulinski et al. reported that adding kurtosis improved the accuracy to predict the probability of temporary threshold shifts for service members at military training facilities ($n = 214$) [23]. In another study, Samardzic et al. highlighted the fact that noise hazardousness is not always related to a higher sound pressure level, based on kurtosis analysis conducted over three workdays for three construction workers [24].

The aforementioned studies have identified a relationship indicating that the risk of NIHL increased when the noise exposure had a high kurtosis level. The upper or lower limit of the noise and kurtosis levels has not been established. If such an interaction exists, it is unclear how to use the kurtosis metric to adjust current noise levels measured by the equal energy principle to accurately predict the risk of hearing loss from complex noise. To update damage-risk criteria for occupational noise exposure, a multifold research approach is proposed. This approach involves (1) examining the excess risk of material hearing impairment caused by complex noise using a data set on Chinese workers, (2) establishing an adjustment coefficient of kurtosis to apply this metric in predicting hearing loss, (3) applying the findings to the U.S. worker population, and (4) developing a method to calculate kurtosis and then integrating it into a sound measurement instrument. To achieve this approach, the very first step is to identify any patterns or relationships between kurtosis and hearing loss across different exposure levels in the Chinese data set. Therefore, the primary objective of this study was to conduct a quantitative analysis that includes validating control data, presenting the distribution characteristics of noise-exposed workers, examining associations between kurtosis and changes in hearing thresholds at various frequencies, and comparing different noise kurtosis adjustment schemes. This study can help evaluate the effect of kurtosis as it pertains to material hearing impairment as defined by the current NIOSH criteria document [4]. In addition, this study explored the application of kurtosis in estimating the extent of hearing loss and its integration into occupational hearing loss prevention programs.

2 | Materials and Methods

This study used a data set on Chinese workers collected through a cross-sectional study [21]. The study protocol was approved by the Ethics Committee of Zhejiang and Jiangsu Province Centers for Disease Control and Prevention (approval reference number: ZJCDC-T-043-R and JSCDCCLL-2017-025). The data sets were provided by collaborators at SUNY Plattsburgh. The data included personal noise exposure recordings of minimal 8-h work shifts, individual pure-tone hearing threshold levels at 0.5, 1, 2, 3, 4, 6, and 8 kHz for each ear, and demographic information such as age and sex of the participants. Information also included the industry, job title, work shift, work schedule, years of exposure, and smoking and drinking habits of each participant.

2.1 | Study Participants

The study encompassed an original sample size of 1544 non-noise-exposed workers and 2611 noise-exposed workers from 12 industries in eastern China, with data collected from 2017 to 2018. The non-noise-exposed participants considered "otologically normal," meaning they had an external auditory canal unconcluded by cerumen and a visible tympanic membrane without any sign or symptoms of ear disease, history of overexposure to noise, exposure to potentially ototoxic substances, or familial hearing loss [25]. These participants included factory office workers, technology company programmers, and healthcare workers. Because of the limited number of participants over 60 years old, this study included a total of 1520 non-noise exposed participants ranging in age from 18 to 60 years.

The noise-exposed workers had specific inclusion criteria. They had no military service history or involvement in shooting activities. In addition, they had a good external auditory canal and tympanic membrane as observed through otoscopic examination. Furthermore, to maintain consistency with previous research documented by NIOSH, noise exposure was limited to a maximum of 102 dBA [4, 5]. Consequently, this study included a total of 2400 noise-exposed workers. Their noise exposure levels, measured as an $L_{\mathrm{Aeq,8h}}$, ranged from 70 to 102 dBA, and their age spanned from 18 to 60 years. It is worth noting that the use of hearing protection devices (HPDs) by the majority of noise-exposed workers was reported to be low and infrequent [21], except 385 workers from an auto parts factory. Those workers used a pre-molded earplug over their work shifts for 6 years. However, no detectable effect was observed in preventing hearing loss through the use of such hearing protectors [26].

2.2 | Personal Noise Exposure Waveform Recordings and Their Analysis

2.2.1 | Personal Noise Exposure Waveform Recordings

Each noise-exposed worker wore an ASV5910-R digital recorder on their shoulder (Hangzhou Aihua Instruments Co., Hangzhou, China). The digital recorder operated continuously with 32-bit resolution at a 48-kHz sampling rate throughout the participants' work shift. The recorders were equipped with a ¼-inch pre-polarized condenser microphone that had a broad response frequency range of 20 Hz to 20 kHz and a high-sensitivity level of 2.24 mV/Pa. Pre- and post-calibrations were performed for each recorder using an AWA6211 sound level calibrator (Hangzhou Aihua Instrument Co., Hangzhou, China). The personal full-shift noise exposure waveform recordings were captured and saved on a 32-GB microSD card in a raw audio format (WAV file). The calibration values for the WAV files are stored within the resource interchange file format structure of the WAV'S header. These recordings were then transferred to a portable hard disk for subsequent analysis. Such analysis was performed using programming tools from MATLAB software (The MathWorks, R2017) specifically designed to analyze and calculate the various metrics described in this study.

2.2.2 | Calculation of $L_{Aeq,8h}$

The calculation of $L_{Aeq,8h}$ followed Equation (2),

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

where T_e is the effective duration of the working day in minutes; and T_0 is the reference duration, set at 480 min.

2.2.3 | Calculation of Kurtosis (βi)

Kurtosis, denoted as β_i, is the fourth moment of the statistical distribution of the sound pressure. In this study, the β_i was computed over nonoverlapping 60-second time windows for the entire recording, as suggested by Tian et al. [14]

$$\beta_i = \frac{\frac{1}{n}\sum_{\omega=1}^{\omega=n}(x_\omega - \overline{X})^4}{\left[\frac{1}{n}\sum_{1\omega=1}^{N\omega=n}(x_\omega - \overline{X})^2\right]^2}, \quad (3)$$

where β_i is the biased kurtosis of the sound pressure at every 60-second interval. n is the number of samples in the 60-second time window, x_ω is the ωth sample of the sound pressure, and $\bar{x}$ is the sample mean. A sinusoidal wave would have an expected β value of 1.5, while a normal distribution would have an expected β value of 3.

To characterize the work-shift noise records, two statistical values of kurtosis were calculated: (a) an arithmetic average of measured kurtosis (β_{ARI}) using Equation (4) a geometric average of measured kurtosis (β_{GEO}) using Equation (5).

$$\beta_{ARI} = \frac{1}{N}\sum_{i=1}^{i=N}\beta_i, \quad (4)$$

where β_{ARI} is the arithmetic average of the β_i for a sample of N values; N refers to the number of kurtosis values (β_i) obtained from the full-shift noise exposure recording. The individual β_i values were calculated at every 60-second interval using Equation (3).

$$\beta_{GEO} = \left(\prod_{i=1}^{i=N}\beta_i\right)^{1/N}, \quad (5)$$

where β_{GEO} is the geometric average of the β_i values calculated for a sample of N values; N is the number of kurtosis values of β_i obtained from the full-shift noise exposure recording. The individual β_i values were calculated at every 60-second interval using Equation (3).

2.3 | Pure-Tone Hearing Threshold Levels and Their Analysis

2.3.1 | Cumulative Distribution of Hearing Threshold of Non-Noise Exposed Participants

The hearing threshold data were reported in values that are multiples of 5, such as −10, −5, 0, 5, 10, and so on. These values were measured in 5-dB increments with a range of ±2.5 dB for each measurement. For example, if a value was reported as 10 dB, it means that the actual hearing threshold level fell within the range of 7.5 to 12.5 dB.

The upper limit method was used to calculate the cumulative distribution of hearing threshold levels by frequency for non-noise-exposed participants. This method, as described by Hoffman et al. [27], involved determining the percentage values of the data that are less than or equal to the upper limit of each value. To calculate percentage values that fall between two values in the list (a lower value and a higher value), each percentage value was determined by adding a fraction of the difference between the higher and lower values to the upper limit of the lower value. For example, to calculate the percentage value for a point between 5 dB to 10 dB, the authors added a fraction (based on the target percentage) of the difference between these two values to the upper limit (10 dB) of the lower value (5 dB).

2.3.2 | Noise-Induced Permanent Threshold Shift Estimation of Noise-Exposed Workers

To calculate the actual noise-induced permanent threshold shift (actual NIPTS) of an individual noise-exposed worker at a specific frequency, the pure-tone hearing threshold levels were adjusted by subtracting the 50% cumulative distribution of hearing threshold from an age- and sex-matched population of non-noise exposed workers.

Two other measures, unadjusted NIPTS and adjusted NIPTS, were estimated for comparison purposes using the equation described in the ISO 1999 [20]. The unadjusted NIPTS at each test frequency was based on measured $L_{Aeq,8h}$, while the adjusted NIPTS was based on kurtosis-adjusted $L_{Aeq,8h}$ ($L'_{Aeq,8h}$). Equation (1) was used to calculate $L'_{Aeq,8h}$ for each frequency.

The major outcome of interest in this study was the NIPTS over frequencies, which represented a binaural average NIPTS level for a selected set of frequencies. Two sets of frequencies were analyzed: (a) $NIPTS_{1234}$ (1, 2, 3, and 4 kHz) and (b) $NIPTS_{346}$ (3, 4, and 6 kHz). $NIPTS_{1234}$ was chosen because it is defined by the current NIOSH criteria document [4], and $NIPTS_{346}$ was defined by Zhang et al. [21].

2.4 | Adjusting $L_{Aeq,8h}$ Using the Noise Kurtosis Values

Using a multiple regression model (Equation 6), the coefficients of kurtosis adjustment (λ) were calculated according to Equation (7) [11].

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

$$\lambda = b_2/b_1, \quad (7)$$

where NIPTS is the actual NIPTS. In the study, two values were used (1) $NIPTS_{1234}$ and (2) $NIPTS_{346}$. 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. β_N is the noise kurtosis value; in this study, two values of β_N are used: (a) the arithmetic average of measured kurtosis (β_{ARI})

in Equation (4) or (b) the geometric average of measured kurtosis (β_{GEO}) in Equation (5). ε is the model's error (residual) term. λ is the kurtosis adjustment coefficient.

The kurtosis-adjusted $L_{Aeq,8h}$ ($L'_{Aeq,8h}$) was calculated as Equation (1). In the study, β_N was replaced with β_{ARI} or β_{GEO} to calculate the arithmetic average of the measured kurtosis-adjusted $L_{Aeq,8h}$ ($L'_{Aeq,8h\_\mathrm{ARI}}$) or geometric average of measured kurtosis-adjusted $L_{Aeq,8h}$ ($L'_{Aeq,8h\_\mathrm{GEO}}$), respectively.

2.5 | Statistical Analysis

In previous studies [15, 18, 21], the dependent variable used was the hearing threshold in the better ear. However, in the NIOSH criteria document [4, 5], the average hearing threshold levels over the left and right ears were used. To determine any differences between the left and right ears of non-noise exposed participants, a paired *t*-test was conducted on their hearing threshold data.

To establish baseline statistics for pure-tone hearing threshold levels, a 50% distribution of hearing threshold at each frequency was calculated from the non-noise exposed participants' data. The participants were divided into five continuous age groups within each sex category. The boundaries for each age group were selected to have a relatively equal size with each category. This division was done to maximize the statistical power [28]. Figures were generated to illustrate these distributions. This analysis helped ensure that the control group used for comparison with the noise-exposed workers was repetitive and unbiased.

For noise-exposed workers, their data were classified into four categories based on noise-exposed categories of 70–79, 80–87, 88–92, and 93–102 dBA. The average noise exposure levels for each category were 76, 85, 90, and 97 dBA. These categories were chosen to align with future risk assessments based on the NIOSH recommended exposure limit (REL) of 85 dBA TWA and the Occupational and Health Administration (OSHA) permissible exposure limit (PEL) of 90 dBA TWA. They also corresponded with previous NIOSH studies [5, 28].

To identify variables that would be included in later linear regression model analysis, a general-purpose procedure for regression (REG procedure) was employed. The average actual NIPTS_{1234} or NIPTS_{346} served as the dependent variable in the analysis. Independent variables included age, exposure duration in the year, $L_{Aeq,8h}$, and $\log_{10}(\beta_{ARI}/3)$ or $\log_{10}(\beta_{GEO}/3)$ to evaluate the relationship with hearing threshold levels. Multiple linear regression was used to examine the effect of kurtosis on NIPTS_{1234} or NIPTS_{346}.

Since kurtosis is distributed primarily in a lognormal manner [22], the bootstrapped procedure (10,000 samples with replacement) was used to estimate the means of kurtosis and their 95% confidence interval (CI). Statistical analyses were performed with SAS (release 9.4, SAS Institute Inc., Cary, NC, USA). A statistical significance level of $p < 0.05$ was adopted for all analyses.

3 | Results

3.1 | Validation of Hearing Threshold Levels for Non-noise-Exposed Participants

This study included a total of 1520 non-noise-exposed participants. Among them, 38% were male and 62% were female. Male participants had a higher average age (40 ± 10.1) compared with the female participants (36 ± 9.4) ($p < 0.001$). The noise levels in their work environment were below 70 dBA as reported by Zhang et al. [21]. None of the participants indicated that they had a history of high-level noise exposure in their workplaces or daily life.

Table 1 presents the results of paired *t*-tests conducted to examine the hearing threshold differences between the left and right ears of non-noise-exposed participants. Statistically significant differences were found at two frequencies: 2 kHz (0.5 dB higher in the left ears, $p = 0.0020$) and 6 kHz (1.5 dB lower in the left ears, $p < 0.001$). However, these differences fell within the audiometry test/retest variability range of ± 5 dB as reported by Flamme et al. [29]. In subsequent analyses, hearing levels for all participants were averaged across both ears, considering that the observed differences between left and right ears were within acceptable limits.

Table 2 presents the 10%, 50%, and 90% distribution of hearing threshold levels of the five age groups within each sex category among non-noise-exposed participants. The table confirms that as age increases, so do the hearing threshold levels across different frequencies. This finding is consistent with age-related hearing loss.

Figure 1 illustrates this trend, showing that male participants aged 36 and above have increased hearing threshold levels across frequencies from 0.5 to 8 kHz. Similarly, female participants aged 39 and above also exhibited increased hearing threshold levels in this frequency range. It is observed that male participants generally have worse hearing compared with female participants. In addition, a V-shaped audiogram notch is observed for all age groups at 6 kHz.

For subsequent analysis, the estimation of the NIPTS in noise-exposed workers was obtained by subtracting the 50% distribution of hearing threshold levels from sex- and age-matched non-noise-exposed participants. This approach allows for comparison and evaluation of the effect of noise exposure on hearing threshold relative to a baseline established by non-noise-exposed individuals.

3.2 | Industry and Occupational Distribution, Noise Exposure Levels, and Hearing Threshold for Noise-Exposed Workers

In the study, a total of 2400 noise-exposed workers were included. These workers were from 13 industries and had 64 different job titles. Most were from motor vehicle parts manufacturers ($n = 872$), followed by furniture and related product manufacturers ($n = 433$). The most common job title was machinist ($n = 497$), followed by woodworking machine setters

TABLE 1 | The differences in hearing threshold levels between left and right ears by frequency among the non-noise-exposed participants ($n = 1520$).

Frequency (kHz)	Mean	Standard deviation (SD)	Minimum	Maximum	*t* Stat	*p* (two-tail)
0.5	−0.1	6.5	−55	30	−0.41	0.6803
1	0.0	6.1	−35	25	0.30	0.7678
2	0.5	6.7	−38	35	3.10	0.0020*
3	−0.1	7.0	−35	25	−0.48	0.6343
4	−0.3	8.5	−40	50	−1.22	0.2238
6	−1.5	10.1	−50	55	−5.96	< 0.001*
8	0.0	10.4	−50	70	0.14	0.8905

*$p < 0.05$.

TABLE 2 | The selected value of accumulative statistical distributions of hearing threshold levels (dB) among the non-noise exposed participants according to frequency (kHz) classified by age and sex ($n = 1520$).

Frequency (kHz)	Percentages														
	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
Male, $n = 576$	G1,[a] 25 (18–29) yrs, $n = 105$			G2,[a] 32 (30–35) yrs, $n = 106$			G3,[a] 38 (36–41) yr, $n = 124$			G4,[a] 46 (42–50) yr, $n = 129$			G5,[a] 54 (51–60) yr, $n = 112$		
0.5	4	10	16	4	11	18	4	10	18	6	12	20	6	13	22
1	4	9	16	2	9	18	1	10	21	5	11	21	5	13	25
2	3	8	15	2	10	19	2	9	19	5	12	22	5	15	26
3	2	9	16	3	11	19	2	13	24	7	16	28	8	19	33
4	2	9	20	1	10	22	2	13	29	7	18	33	9	21	48
6	8	18	32	8	18	30	10	21	38	15	25	45	18	30	54
8	3	10	25	3	12	27	6	15	35	11	21	43	11	26	54
Female, $n = 944$	G1,[b] 24 (18–27) yr, $n = 184$			G2,[b] 30 (28–32) yr, $n = 211$			G3,[b] 35 (33–38) yr, $n = 192$			G4,[b], 42 (39–46) yr, $n = 184$			G5[b], 50 (47–60) yr, $n = 176$		
0.5	5	10	17	4	10	16	4	9	17	4	11	21	8	12	22
1	3	9	16	2	9	16	2	8	17	3	10	21	5	12	24
2	3	9	17	2	9	18	2	9	17	3	11	22	7	14	25
3	2	9	17	2	10	18	2	9	20	5	11	22	6	16	26
4	1	7	15	−2	9	17	2	9	19	1	11	23	5	14	24
6	9	16	26	8	17	26	11	19	29	11	21	35	14	25	37
8	3	9	19	2	9	20	4	12	23	5	15	34	10	20	37

[a]There are five age groups among male participants, each with relatively equal sizes. For example, G1 (Group 1) has a mean age of 25 years (range: 18–29), and so on.
[b]Similarly, there are five age groups among female participants, each with relatively equal sizes. For example, G1 (Group 1) has a mean age of 24 years (range: 18–27), and so on.

($n = 285$). Among them, 81% were male and 19% were female. The average age of the male participants (34 ± 5.9) was lower than female participants (38 ± 5.9) ($p < 0.001$).

To compare the hearing threshold distributions between non-noise-exposed participants and complex noise-exposed workers, the noise-exposed workers were divided into five continuous age groups within each sex category. The boundaries for each age group were selected to have a relatively equal size with each category. The results are presented in Table 3 and Figure 2. Table 3 shows that the subgroups within each sex group were exposed to relatively similar noise exposure levels and kurtosis values. It clearly shows that female workers had lower average noise exposure levels and lower kurtosis values when compared with male participants. Figure 2 displays the 50% distribution of hearing threshold levels for noise-exposed workers by frequency and age group. It is observed that male participants generally have worse hearing compared with female participants, which is consistent with the results from non-noise exposed participants. However, broader notches that extended towards 4 kHz and formed a U-shape are observed for the male workers, while audiogram notches at 6 kHz are continually observed for female workers.

3.3 | Noise Kurtosis Contribution to Actual NIPTS

Table 4 provides a summary of the age, $L_{Aeq,8h}$, Arithmetic average of kurtosis (β_{ARI}), and exposure duration of four

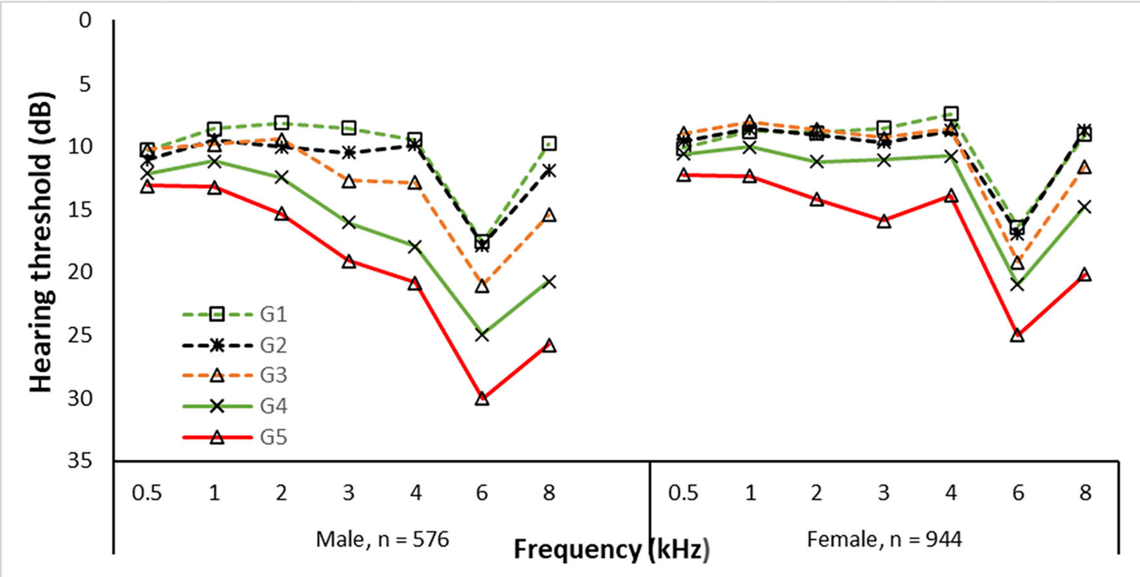

FIGURE 1 | Comparison of the 50% distribution of hearing threshold levels between male and female non-noise exposed participants, categorized by frequency and age group. Note: The mean age (with range) for each group is presented in Table 2. For male participants, the mean ages (ranges) are as follows: G1 is 25 years (18–29), G2 is 32 years (30–35), G3 is 38 years (36–41), G4 is 46 years (42–50), and G5 is years 54 (51–60). For female participants, the mean ages are as follows: G1 is 24 years (18–27), G2 is 30 years (28–32), G3 is 35 years (33–38), G4 is 42 years (39–46), and G5 is 50 years (47–60).

TABLE 3 | Summary of age, noise exposure level, measured kurtosis, and exposure duration by sex and age among noise-exposed workers ($n = 2400$).

Age group (yr)	n	Age (yr) mean ± SD	$L_{Aeq,8h}$ (dBA) mean ± SD	Duration (yr) mean ± SD	β_{ARI} mean (95% CI)	β_{GEO} mean (95% CI)
Male	1,940	34.1 ± 9.8	88.1 ± 5.9	6.4 ± 5.7	67.8 (62.8, 73.2)	23.8 (22.1, 25.5)
G1 (18–25)	392	22.5 ± 2.1	86.9 ± 5.7	2.8 ± 1.5	88.1 (74.0, 103.0)	29.7 (25.6, 34.1)
G2 (26–30)	446	28.2 ± 1.4	87.3 ± 5.2	4.4 ± 2.9	71.0 (59.9, 82.9)	25.0 (21.5, 28.9)
G3 (31–36)	363	33.4 ± 1.8	87.9 ± 6.1	6.3 ± 3.7	67.6 (54.8, 82.0)	24.3 (20.1, 28.9)
G4 (37–44)	363	40.3 ± 2.3	89.4 ± 2.0	7.7 ± 5.0	61.0 (51.6, 71.3)	22.6 (19.4, 26.2)
G5 (45–60)	376	49.9 ± 4.0	89.3 ± 6.3	11.8 ± 7.7	49.6 (43.5, 56.3)	16.6 (14.8, 18.7)
Female	460	38.0 ± 8.2	86.4 ± 7.1	6.8 ± 5.4	37.3 (32.8, 42.5)	15.1 (13.8, 16.6)
G1 (19–30)	95	26.1 ± 3.4	83.6 ± 7.2	2.8 ± 2.0	51.4 (35.8, 71.4)	18.1 (14.8, 18.2)
G2 (31–36)	96	33.5 ± 1.7	86.4 ± 5.3	5.0 ± 4.0	31.0 (24.9, 38.6)	14.5 (11.8, 18.2)
G3 (37–41)	89	39.0 ± 1.3	86.9 ± 5.1	7.4 ± 4.7	36.5 (28.5, 46.9)	15.2 (12.1, 18.9)
G4 (42–45)	89	43.3 ± 1.1	87.5 ± 4.5	8.7 ± 5.0	29.6 (23.1, 37.6)	12.5 (10.6, 14.7)
G5 (46–60)	91	49.0 ± 2.6	87.7 ± 6.0	10.7 ± 6.9	37.8 (29.3, 48.0)	15.2 (12.7, 18.2)
Total	2400	35.3 ± 9.6	87.8 ± 5.9	6.4 ± 5.6	62.0 (57.7, 66.5)	22.1 (20.8, 23.5)

Note: CI, confidence interval; SD, standard deviation.

different noise-exposed groups: 70–79, 80–87, 88–92, and 93–102 dBA. The differences in exposure duration and age were relatively close except for the highest noise exposure group. 41.8% of workers were exposed to noise levels of 80–87 and 32.3% to 88–92 dBA.

Within each group, the data were further divided into 10 continuous kurtosis subgroups with a relatively similar sample size. It was ensured that each subgroup had a minimum sample size of 30 participants to maintain statistical reliability [28]. However, for workers exposed to noise levels ranging from 70 to 79 dBA, only seven kurtosis subgroups could be obtained because of the limited sample size. Figure 3 presents the relationship between the mean of actual NIPTS and the mean of measured arithmetic average kurtosis (β_{ARI}) across different frequencies (0.5–8 kHz). The figure shows a clear trend where the mean of actual NIPTS increased as the mean of β_{ARI} increased from 0.5 to 8 kHz. The actual NIPTS with the lowest kurtosis value (K1, represented by a black dashed line) and those with the highest kurtosis value (K7 for the 70–79 dBA group, represented by a purple dashed line; K10 for the other noise groups,

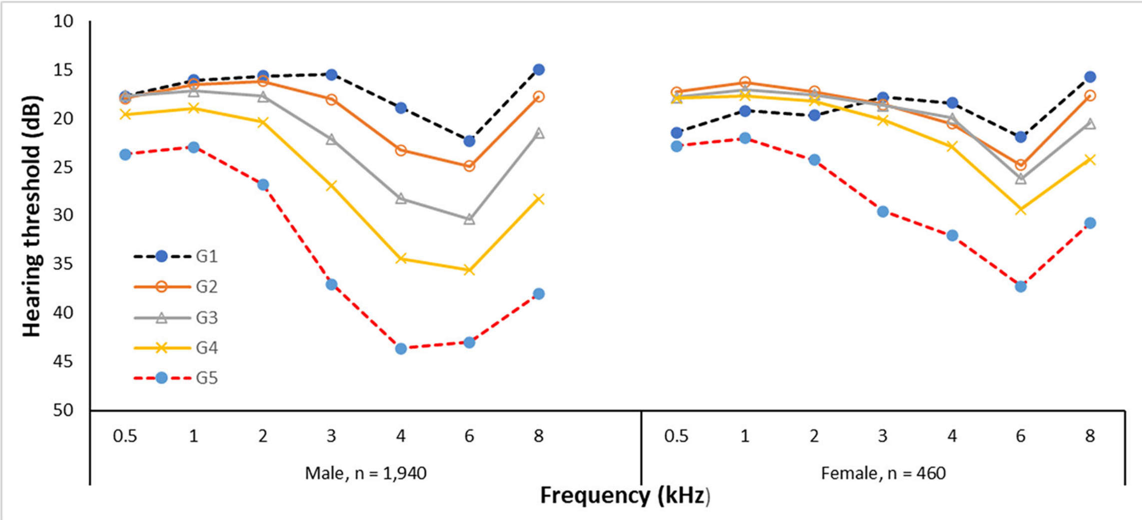

FIGURE 2 | Comparison of the 50% distribution of hearing threshold levels among noise-exposed workers between male workers (left panel) and female workers (right panel) by frequency and age. *Note:* The mean age (with range) for each group is presented in Table 3. For male participants, the mean ages are as follows: G1 is 22 years (18–25), G2 is 28 years (26–30), G3 is 33 years (31–36), G4 is 40 years (37–44), and G5 is years 50 (45–60). For female participants, the mean ages are as follows: G1 is 26 years (19–30), G2 is 33 years (31–36), G3 is 39 years (37–41), G4 is 43 years (42–45), and G5 is 49 years (46–60).

TABLE 4 | Mean and SD of age, noise exposure level, arithmetic average of kurtosis, and exposure duration of 4 noise exposure groups ($n = 2400$).

Noise group	*n* (%)	Age (yr) mean ± SD	$L_{Aeq,8h}$ (dBA) mean ± SD	Duration (yr) mean ± SD	β_{ARI} mean (95% CI)
70 dBA ≤ N1 < 80	224 (9.3)	33 ± 11	76 ± 3	6 ± 7	49.0 (40.1, 60.4)
80 dBA ≤ N2 < 88	1004 (41.8)	35 ± 10	85 ± 2	7 ± 6	51.6 (47.0, 56.5)
88 dBA ≤ N3 < 92	774 (32.3)	35 ± 9	90 ± 1	6 ± 5	73.0 (64.0, 82.5)
92 dBA ≤ N4 < 103	398 (16.6%)	38 ± 10	97 ± 3	6 ± 5	73.9 (61.1, 87.5)

Note: CI, confidence interval; SD, standard deviation.

represented by a red dashed line) are clearly separated from each other from 3 to 8 kHz. However, some overlapping is observed from 0.5 to 2 kHz.

In addition, a sharp audiometric V-notch is observed at 4 kHz for all groups, which is different from the notches at 6 kHz for the non-noise exposed participants. This indicates that there is a significant effect on hearing threshold at this specific frequency across different noise exposure levels and kurtosis values.

The effects of kurtosis are further evidenced when plotting the average actual $NIPTS_{1234}$ of kurtosis subgroups against the logarithm base 10 of the arithmetic average of measured kurtosis [$\log_{10}(\beta_{ARI}/3)$], except for the noise group of 70–79 dBA. It is observed that the average $NIPTS_{1234}$ values of the 70–79 dBA noise exposure group overlap with those of the 88–92A and 93–102 dBA noise exposure groups (Figure 4). Consequently, data from the 70–79 dBA noise exposure group were excluded from further analysis. This decision was made to reduce the potential confounding factors that could arise from the overlapping nature of their NIPTSs. In addition, some overlapping is observed between the 88–92 dBA noise exposure group and the 93–102 dBA group when considering subgroups with $\log_{10}(\beta_{ARI}/3)$ at 0.6 or below (corresponding to β_{ARI} values at or below 12).

Similar observations were made when using the geometric average of measured kurtosis (β_{GEO}) instead of β_{ARI}, as well as when actual $NIPTS_{1234}$ was substituted with actual $NIPTS_{346}$. However, these results are not presented in the manuscript to avoid redundancy.

3.4 | Multiple Linear Regression Analyzes Kurtosis Contribution to NIPTS

The data points from Figure 3 (except the data from the noise group of 70–79 dBA) were used for the multiple regression analysis to analyze the effect of kurtosis on NIPTS. Initially, a general-purpose procedure for regression was performed using the average actual $NIPTS_{1234}$ or $NIPTS_{346}$ as a dependent variable. The independent variables included age, work duration, $L_{Aeq,8h}$, and kurtosis value of either $\log_{10}(\beta_{ARI}/3)$ or $\log_{10}(\beta_{GEO}/3)$.

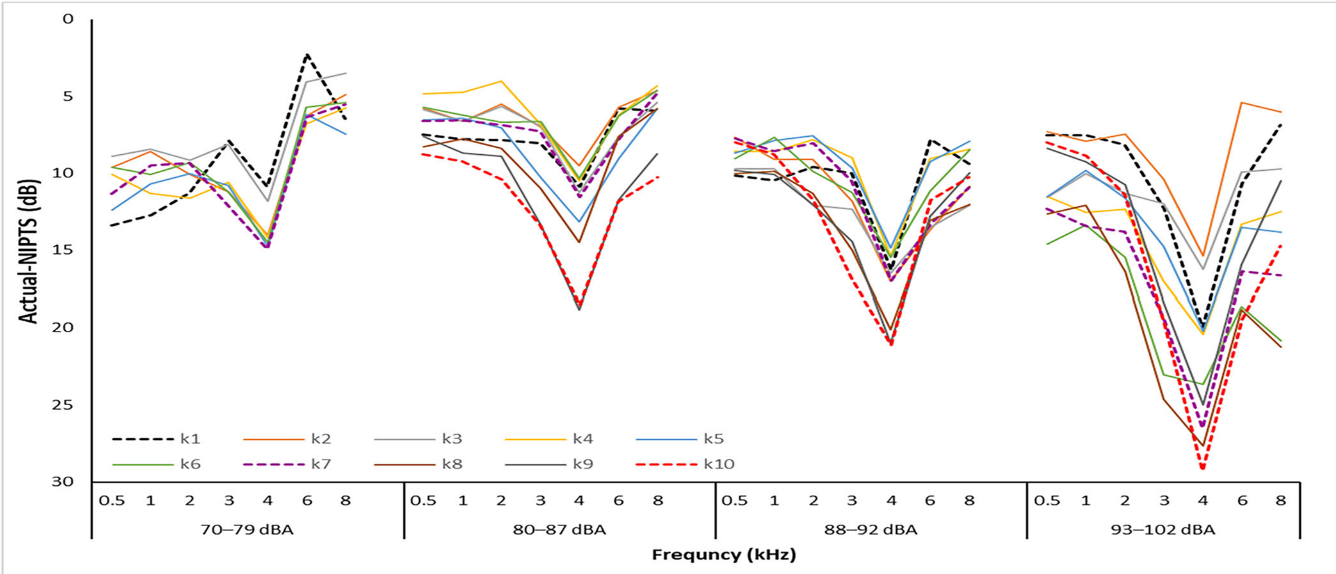

FIGURE 3 | Comparison of the mean of actual noise-induced permanent hearing loss (actual NIPTS) from 0.5 kHz to 8 kHz among noise-exposed workers by arithmetic average kurtosis value (β_{ARI}) for four noise exposure groups (70–79, 80–87, 88–92, and 93–102 dBA). In the 70–79 dBA group, only seven subgroups were obtained based on the average β_{ARI} value. For the other three higher noise exposure groups, 10 subgroups were obtained. Each subgroup within a specific noise group had a similar sample size of at least 30 participants to maintain statistical reliability. The black dashed line represents the K1 subgroup with the lowest kurtosis value, and the red dashed line represents the K10 subgroup with the highest kurtosis value.

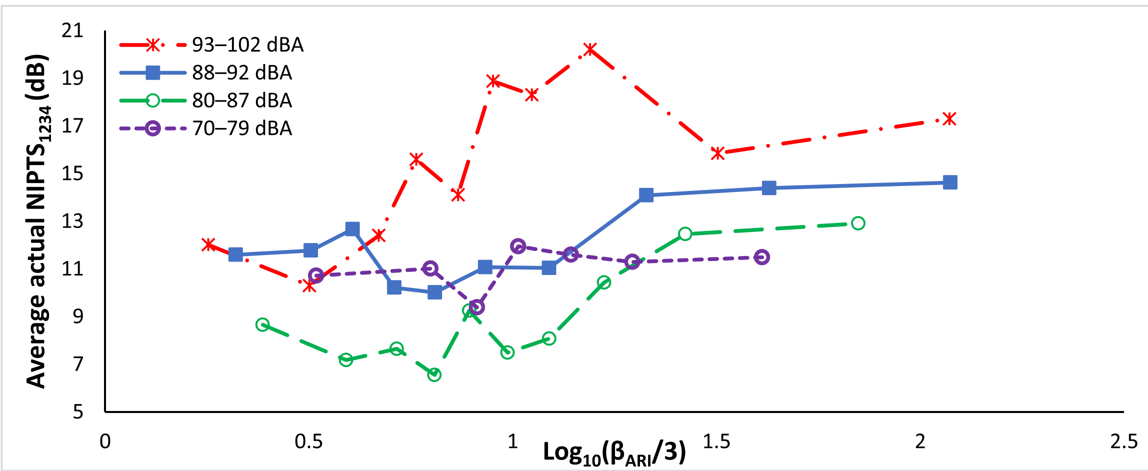

FIGURE 4 | Scatterplot showing that average actual noise-induced permanent hearing loss over 1 kHz and 4 kHz ($NIPTS_{1234}$) increased as noise exposure levels and the arithmetic average of measured kurtosis (β_{ARI}) increased, except for the participants exposed to noise levels between 70 and 79 dBA.

Table 5 represents the results of this initial regression analysis. It shows that there is no statistically significant relationship between age and actual $NIPTS_{1234}$ or $NIPTS_{346}$. This was expected since the actual NIPTS were obtained by subtracting from the 50% distribution of hearing threshold levels based on age- and sex-matched non-noise exposed participants. The inclusion of age as an independent variable did not significantly improve the model fit in this case.

However, the results from noise exposure duration are not consistent across both actual $NIPTS_{1234}$ and $NIPTS_{346}$ ($p = 0.0457$, 0.047, 0.056, and 0.418, respectively). Given the marginally statistically-significant inconsistent results, along with previous study findings [21], it was decided to exclude noise exposure duration from further analysis.

Ultimately, noise exposure levels and average kurtosis values were used as independent variables in the multiple linear regression models presented in Table 6, where the noise exposure level ($L_{Aeq,8h}$) measurements were collapsed into 1-dB bins.

Table 6 demonstrates that using both $L_{Aeq,8h}$ and average kurtosis values strongly predicts NIHL with a coefficient of

TABLE 5 | The results of general-purpose procedures for regression using $NIPTS_{1234}$ or $NIPTS_{346}$ as dependent variables with age, duration, $L_{Aeq,8h}$, and kurtosis value [$\log_{10}(\beta_{ARI}/3)$ or $\log_{10}(\beta_{GEO}/3)$] as independent variables.

Variables Dependent	Independent	Coefficients	Standard error	*t* Stat	*p*-value	Lower 95% boundary	Upper 95% boundary
$NIPTS_{1234}$	Age	0.253	0.243	1.041	0.308	−0.248	0.754
	duration	0.364	0.482	0.755	0.457	−0.629	1.358
	$L_{Aeq,8h}$	0.493	0.098	5.016	< 0.001*	0.291	0.696
	$\text{Log}_{10}(\beta_{ARI}/3)$	3.972	0.649	6.122	< 0.001*	2.636	5.308
$NIPTS_{1234}$	Age	−0.027	0.251	−0.109	0.914	−0.544	0.489
	duration	1.224	0.587	2.085	0.047*	0.015	2.434
	$L_{Aeq,8h}$	0.712	0.105	6.759	< 0.001*	0.495	0.929
	$\text{Log}_{10}(\beta_{GEO}/3)$	7.166	1.002	7.150	< 0.001*	5.102	9.230
$NIPTS_{346}$	Age	0.063	0.274	0.229	0.821	−0.502	0.627
	duration	1.088	0.544	2.001	0.056	−0.032	2.208
	$L_{Aeq,8h}$	0.690	0.111	6.230	< 0.001*	0.462	0.919
	$\text{Log}_{10}(\beta_{ARI}/3)$	5.975	0.731	8.169	< 0.001*	4.469	7.481
$NIPTS_{346}$	Age	0.171	0.238	0.718	0.480	−0.320	0.662
	duration	0.459	0.558	0.823	0.418	−0.690	1.609
	$L_{Aeq,8h}$	0.516	0.100	5.161	< 0.001*	0.310	0.723
	$\text{Log}_{10}(\beta_{GEO}/3)$	4.657	0.952	4.889	< 0.001*	2.695	6.618

*$p < 0.05$.

TABLE 6 | Results of linear regression models using $L_{Aeq,8h}$ *and average kurtosis values* to estimate Actual $NIPTS_{1234}$ or actual $NIPTS_{346}$.

Regression models	Coefficients B	Standard error	B Lower 95%	B Upper 95%	*t* Stat	*p*-value	R^2	*F*	λ (b_2/b_1)
Model 1: $NIPTS_{1234} = b_0+b_1L_{Aeq,8h}+b_2\log_{10}(\beta_{ARI}/3)$							0.7876	50.06	6.1
Intercept	−42.34	5.93	−54.50	−30.18	7.14	0.00			
$L_{Aeq,8h}$	0.56	0.06	0.43	0.70	8.73	0.00			
$\log_{10}(\beta_{ARI}/3)$	3.44	0.66	2.09	4.80	5.21	0.00			
Model 2: $NIPTS_{1234} = b_0+b_1L_{Aeq,8h}+b_2\log_{10}(\beta_{GEO}/3)$							0.7771	47.06	6.5
Intercept	−40.90	5.86	−52.93	−28.87	6.98	0.00			
$L_{Aeq,8h}$	0.56	0.06	0.43	0.69	8.74	0.00			
$\log_{10}(\beta_{GEO}/3)$	3.62	0.81	1.96	5.27	4.48	0.00			
Model 3: $NIPTS_{346} = b_0+b_1L_{Aeq,8h}+b_2\log_{10}(\beta_{ARI}/3)$							0.8071	56.50	7.2
Intercept	−53.97	7.20	−68.75	−39.19	7.49	0.00			
$L_{Aeq,8h}$	0.69	0.08	0.53	0.85	8.83	0.00			
$\log_{10}(\beta_{ARI}/3)$	5.01	0.80	3.36	6.66	6.24	0.00			
Model 4: $NIPTS_{346} = b_0+b_1L_{Aeq,8h}+b_2\log_{10}(\beta_{GEO}/3)$							0.8175	60.47	7.9
Intercept	−51.53	6.61	−65.10	−37.96	7.79	0.00			
$L_{Aeq,8h}$	0.68	0.07	0.53	0.83	9.44	0.00			
$\log_{10}(\beta_{GEO}/3)$	5.40	0.91	3.53	7.27	5.93	0.00			

determination R^2 ranging from 0.78 to 0.82 for the four linear regression models. When predicting $NIPTS_{1234}$, the adjustment coefficients (λ) are 6.1 for β_{ARI} and 6.5 for β_{GEO}, respectively. When predicting NIHL at higher frequencies ($NIPTS_{346}$), the adjustment coefficients (λ) are 7.2 for β_{ARI} and 7.9 for β_{GEO}, respectively. The higher adjustment coefficients observed at higher frequencies suggest that kurtosis has a greater impact on hearing loss within these higher frequency ranges.

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

Figure 5 shows the comparison between unadjusted NIPTS, four kurtosis-adjusted NIPTS estimates, and actual NIPTS by frequency for three noise exposure groups.

For participants exposed to measured $L_{Aeq,8h}$ ranging from 80 to 92 dBA, the unadjusted NIPTS is largely underestimated when compared with the actual NIPTS. The mean underestimation across frequencies from 0.5 to 6 kHz was 7.4 dB, with a range of 5.7 to 9.1 dB. For participants exposed to noise levels between 93 and 102 dBA, there is a relatively small mean underestimation of 5.5 dB over the same frequency range. However, at high frequencies (from 3 to 6 kHz), the lower mean underestimation of 2.7 was observed, varying from 0.5 dB at 6 kHz to 4.9 dB at 4 kHz. In contract, a bigger underestimation of 8.3 dB was noted at lower frequencies (from 0.5 to 2 kHz), with values ranging from 7.0 to 10.8 dB.

After applying kurtosis-adjusted $L_{Aeq,8h}$ values ($L'_{Aeq,8h}$), the estimated adjusted NIPTS are closer to the actual NIPTS. However, none of the four adjusted NIPTS are perfectly matched to the actual NIPTS, especially at frequencies of 2 kHz or below.

For participants in the measured $L_{Aeq,8h}$ range of 80–87 dBA exposure group, using a geometric average kurtosis ($\lambda = 7.9$) to adjust $L_{Aeq,8h}$ resulted in adjusted NIPTS estimates that closely aligned with the actual NIPTS over frequencies from 3 kHz to 6 kHz. For participants in the measured $L_{Aeq,8h}$ range of 88 to 92 dBA exposure group, using an arithmetic average kurtosis ($\lambda = 6.1$) provided adjusted NIPTS estimates that overlapped with actual NIPTS over frequencies from 3 to 6 kHz.

However, for participants in the measured $L_{Aeq,8h}$ range 93–102 dBA exposure group, all adjusted NIPTS estimates were overestimated compared with the actual NIPTS over frequencies from 3 to 6 kHz.

3.6 | Implications for REL of 85 dBA and PEL of 90 dBA

The average noise-exposed levels in the 80–87 dBA group and 88–92 dBA group were 85 and 90 dBA, respectively (Table 4). These data were used to illustrate the implications of the current NIOSH REL of 85 dBA TWA and OSHA PEL of 90 dBA TWA for workers exposed to complex noise.

When arithmetic average kurtosis coefficients (λ) of 6.1 were applied to adjust measured $L_{Aeq,8h}$ values, the number of participants exposed to 85 dBA and above increased from 1311 to 1757. Similarly, the number of participants exposed to 90 dBA and above increased from 393 to 1379. This means that an additional 446 participants (a 25% increase) would need to be included in the hearing loss prevention program (HLPP) when following the NIOSH recommendations [4]. Alternatively, an

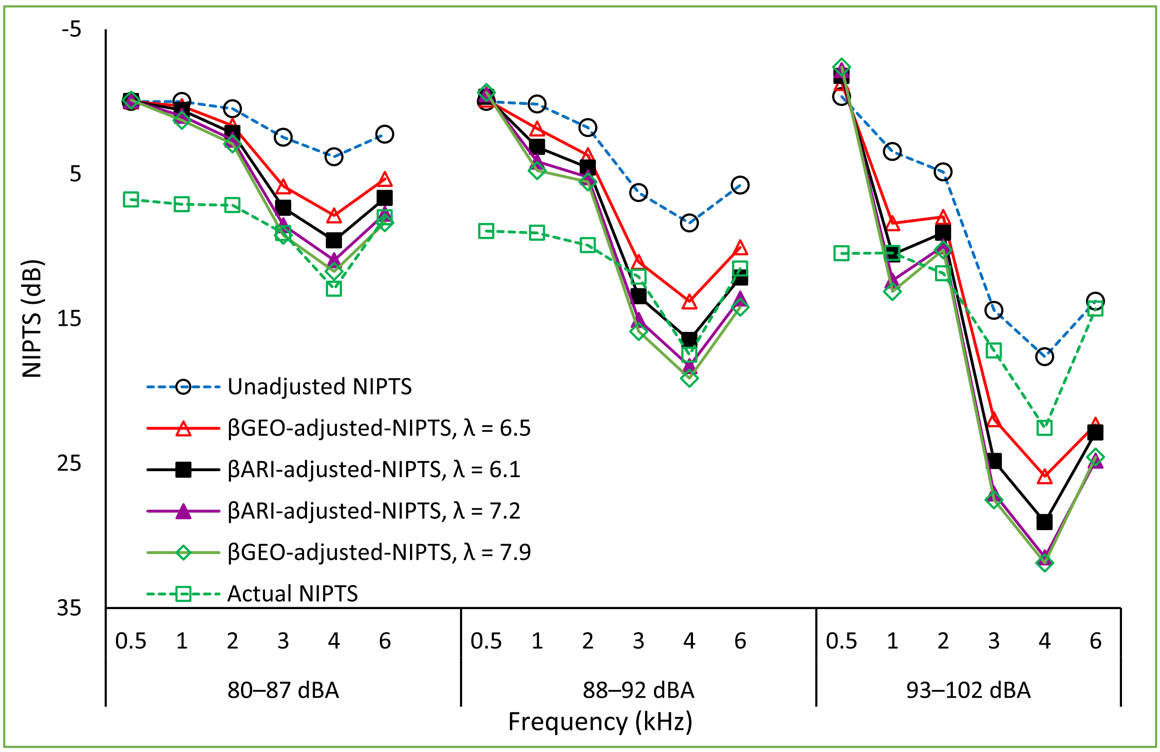

FIGURE 5 | Visualized comparisons of estimation of mean noise-induced permanent hearing loss (estimated NIPTS) with actual NIPTS among noise-exposed workers by noise exposure groups and frequency. The unadjusted NIPTS were estimated using the measured $L_{Aeq,8h}$ [19]. Unadjusted estimates do not consider the effect of kurtosis on hearing loss. The adjusted NIPTS were estimated using kurtosis-adjusted $L_{Aeq,8h}$, which incorporates the effect of kurtosis on hearing loss. The kurtosis coefficients (λ) used in the adjustment were 6.1, 6.5, 7.2, and 7.9.

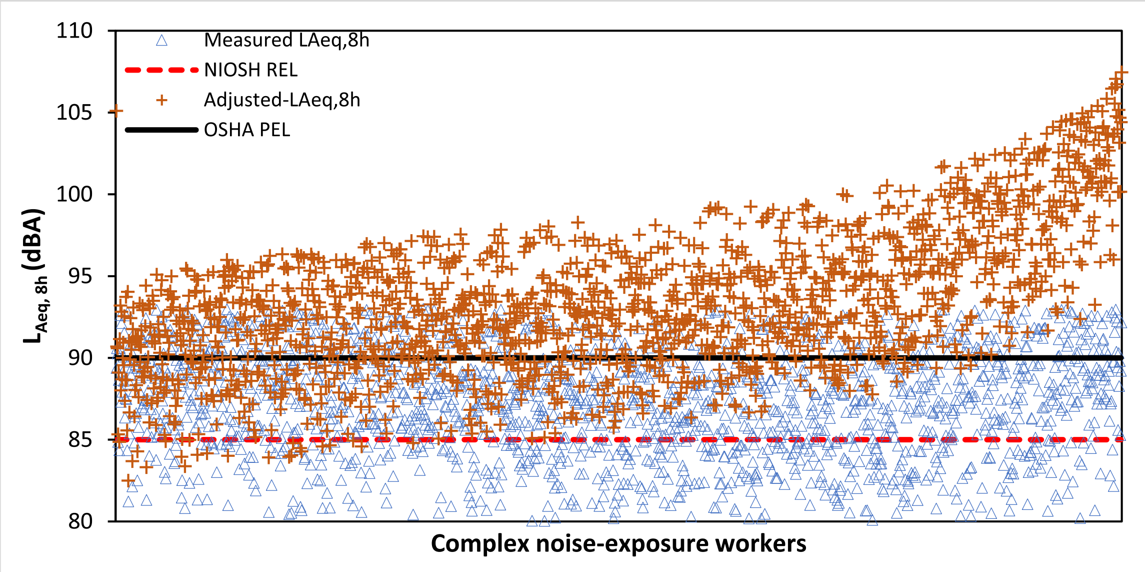

FIGURE 6 | Scatter plot of measured $L_{Aeq,8h}$ (blue triangles) and adjusted-$L_{Aeq,8h}$ values (orange crosses) for noise-exposed workers who were exposed to a range of measured $L_{Aeq,8h}$ from 80 to 92 dBA. The horizontal axis is individual noise-exposed workers sorted by the arithmetic average of measured kurtosis β_{ARI}. The adjusted $L_{Aeq,8h}$ values are obtained by applying a kurtosis coefficient (λ) of 6.1 to measured $L_{Aeq,8h}$ values. The solid black line represents the OSHA PEL of 90 dBA, and the red dashed line represents the NIOSH REL of 85 dBA.

additional 1386 (78% increase) would need to be included in a hearing loss conservation program if adhering to OSHA PEL of 90 dBA TWA (Figure 6).

4 | Discussion

This study aimed to conduct a quantitative examination of the contribution of noise kurtosis to human hearing loss using current human data. It started with a validation of control data to establish baseline statistics for comparison with the noise-exposed workers. The patterns between kurtosis and hearing loss were presented through tables and figures to identify key areas for further analysis in the Chinese data set.

4.1 | Validation of Hearing Threshold Levels of Non-noise-Exposed Participants

In previous research on kurtosis using human data, various approaches were employed to determine the NIPTS, such as (1) subtracting age-related hearing loss defined in ISO 1999 [15, 16, 19, 30] or (2) subtracting normal median hearing threshold levels of age- and sex-matched non-noise-exposed participants, as described in this study [17, 21]. In addition to different approaches for determining NIPTS, researchers have also employed various methods to assess hearing thresholds in their studies, such as those conducted by Davis et al. [30], Tian et al. [14], and Zhao et al. [31], which used the average hearing thresholds of both the left and right ear. On the other hand, studies like Zhang et al [16] and Zhao et al. [31] focused on the hearing threshold of either ear. Furthermore, some researchers chose to assess the hearing threshold of the better ear [17, 22, 32]. Although selecting the better ear may not represent an individual's true hearing, it has been referenced due to the criteria established by ISO 1999:2013, as mentioned by Hoffman et al. [27], or it may be attributed to a conservative approach taken by the researchers [32].

In this study, the control data from the non-noise exposed participants was used as a baseline for further analysis of noise-exposed data. To establish this baseline, the hearing threshold levels between the left and right ears of the non-noise exposed participants were compared. Although statistically significant differences in hearing threshold levels at 2 and 6 kHz were found, these differences fell within the variability observed in audiometry test measurement (±5 dB) [29], indicating that the differences in hearing threshold between the left and right ears were not clinically significant. Therefore, averaging the hearing threshold levels across both ears for all participants is a reasonable approach and consistent with NIOSH guidance [4, 5].

The validation of hearing threshold levels in non-noise-exposed participants further supports the reliability of the control data. The observed characteristics, including an increase in hearing threshold with age, a sharp V-notch at 6 kHz, and worse hearing in the male participants compared with the female participants, align with findings from ISO 1999: 2013 standard [20] and unscreened populations in the United States [33]. This validation strengthens the use of control data as a baseline for further analysis.

4.2 | Observation of Complex Noise Impact on Noise-Induced Permanent Hearing Loss

Results from this study show that fewer female workers were employed in various industries and occupations compared with male workers. In addition, female workers were exposed to lower noise and lower noise kurtosis compared with male workers. The audiometric V-notch at 6 kHz for female noise-exposed workers, which is shallower compared with the V-notch observed in the female control population. On the other hand, male noise-exposed workers exhibited a broadened audiometry V-notch towards 4 kHz, forming a U-shape compared with the male control population. This suggests that complex noise exposure may have a greater effect on hearing loss at 4 kHz, especially considering that male noise-exposed workers were exposed to higher levels of complex noise with higher kurtosis levels compared with female noise-exposed workers.

This observation was further supported by the NIPTS by frequency. The audiometric notch of the noise-exposed workers shifted from 6 to 4 kHz, indicating significant damage to hearing at this frequency due to complex noise exposure. Moreover, as noise kurtosis increased within each noise group, NIPTS worsened over the range of frequencies from 3 to 8 kHz. However, overlap was observed for hearing levels at 2 kHz or below.

These findings suggest that complex noise may have varying effects on hearing at different frequencies, with 4 kHz being particularly sensitive. This finding is consistent with a study by Martin and Gibson [6] on complex noise and its effect on hearing.

Results from this study show that as noise exposure and kurtosis values increase, $NIPTS_{1234}$ also increases, except for the data from the 70–79 dBA noise exposure group. Because of this inconsistency, the data from the 70–79 group were excluded from further analysis. This finding contradicts a report by Zhang et al. [21], which suggested that an $L_{Aeq,8h}$ of 70 dBA is the threshold for the effect of kurtosis. One possible explanation for this discrepancy is the limited sample size of the 70–79 dBA noise exposure group in this study. Future data collection efforts could focus on better characterization of dose–response relationships, including workers exposed to $L_{Aeq,8h}$ levels below 80 dBA.

4.3 | Quantitative Analysis of Kurtosis

Contribution to NIPTS

The general-purpose procedure used in this study did not consistently show statistically significant effects on hearing loss when work duration was used as an independent variable. This finding disagrees with other studies, such as the one by Mantysalo and Vuori [7], which suggested that impulse noise (in shipyards) may lead to permanent threshold shifts after a shorter duration of exposure compared with continuous steady-state noise. In addition, another study reported that the prevalence of NIHL at 0.5, 1, and 2 kHz among manufacturing workers was related to age and noise exposure duration [34]. However, Zhang et al. [21] reported that including exposure duration did not significantly improve the multiple linear regression model for estimating NIPTS. Given these inconsistent findings, it may be beneficial to further study the impact of exposure duration on excess risk assessment related to complex noise.

When different values of noise kurtosis coefficients were applied to adjust measured noise levels, the estimated adjusted NIPTS values were closer to actual NIPTS over the range of frequencies from 3 kHz to 6 kHz for workers in the noise groups of 80–87 dBA and 88–92 dBA compared with estimated unadjusted NIPTS. However, none of the four applied coefficients were perfect in their estimation. Additionally, the estimated adjusted-NIPTS at or below 2 kHz were closer to unadjusted NIPTS values, suggesting that kurtosis contributes less weight to NIHL at lower frequencies and that using NIPTS values at higher frequencies would be more sensitive for the risk assessment analysis.

For workers exposed to noise levels of 93 dBA or above, the adjusted NIPTS values were overestimated compared with the actual NIPTS values over 3–6 kHz. One reasonable explanation is that noise energy may dominate the hearing damage when noise levels reach or exceed 95 dBA. Another plausible explanation is that workers may often effectively wear HPD when L_{eq} was equal to or greater than 95 dBA [21, 35].

4.4 | Application of Kurtosis-Adjusted Noise Exposure Levels to Hearing Conservation Programs

Noise exposure and occupational NIHL remain highly prevalent worldwide [36]. In the United States, 47% of workers in the manufacturing sector are exposed to occupational noise [1], and 18% of these workers with material hearing impairment reported experiencing hearing difficulty [37]. Despite the implementation of hearing conservation programs over several decades, the trend of hearing loss in the manufacturing sector remains stable [37]. This suggests that current noise measurement may not be effectively addressing the problem.

The overall noise kurtosis for all industries investigated was 62. When using the selected kurtosis coefficient to adjust measured noise exposure, it was found that an additional 25% of the complex noise-exposed workers should be recommended for inclusion in a hearing loss prevention program [4], and an additional 78% should be included in a hearing conservation program [38]. This finding suggests that underestimating the hearing loss caused by complex noise may be one of several reasons why the effectiveness of hearing conservation programs is reduced.

The contribution of kurtosis to the effectiveness of a hearing conservation program can be further supported by the different kurtosis values in various industries. Masterson et al. reported that two industries, wood product manufacturing and machinery manufacturing, had a higher risk of hearing impairment (65% and 56% higher) compared with a reference industry [39]. This study also found that furniture and related product manufacturing and metalworking machinery manufacturing had the highest average kurtosis levels of 196 and 72 (data not reported), respectively.

The goal of a hearing conservation program is to prevent occupational NIHL. To achieve this goal, it is crucial to identify workers at risk of hearing loss and include them in the hearing conservation program. Figure 6 demonstrates that using kurtosis to adjust measured noise exposure levels can help identify workers who may be overexposed to complex noise and should be recruited into the program. This is particularly important for workers exposed to complex noise levels at or below NIOSH REL or OSHA PEL, as their hearing risk is likely underestimated using existing noise measurement technologies.

By considering kurtosis as an additional predictor in assessing complex noise exposure, organizations can better target their efforts towards workers who may be more susceptible to the damaging effects of complex noise. The approach can enhance the effectiveness of hearing conservation programs in preventing occupational NIHL. Meanwhile, manufacturers could consider including the kurtosis metric in sound measurement equipment.

4.5 | Considerations Future Data Analysis

The results from this quantitative analysis provide valuable insights and suggest several research directions.

First, further quantitative analysis could evaluate the potential hearing damage from exposure to complex noise and assess the excess risk of hearing loss in participants exposed to noise levels of 80 dBA and above, It is especially crucial to identify workers exposed to average noise levels of 85 and 90 dBA at risk of hearing loss and to include them in the hearing conservation program. This will help further determine the implications of complex noise exposure for the effectiveness of a hearing conservation program.

Second, including a control group consisting of participants exposed to continuous noise (kurtosis value equals 3) could enhance the risk assessment of complex noise to hearing loss. The NIOSH Occupational Noise and Hearing Survey Data [5] could be used for this purpose. In addition, sensitivity analyses could allow for comparisons between different dose–response relationships, definitions of hearing loss, kurtosis adjustment schemes, and noise exposure durations. This could help determine the effectiveness threshold and categories for kurtosis across different levels of noise exposure.

Third, it is important to validate the effectiveness of kurtosis in predicting hearing loss. This could be achieved by applying the study results to other surveillance databases, such as the National Health and Nutrition Examination Survey (NHANES) data on hearing loss within the same industry/occupation. Since current commercial sound level meters and noise dosimeters cannot report the noise kurtosis values as described in the study, validation efforts could be beneficial.

Finally, since kurtosis is frequency-dependent, it could be beneficial to conduct detailed analyses to explore kurtosis effects on hearing loss at different frequencies. It is also important to assess the excess risk of hearing loss at each frequency contributed by kurtosis.

5 | Conclusions

No clinical difference in hearing threshold levels between the left and right ears in the study data set was observed. This finding allowed for the use of an average hearing threshold of both ears as an independent variable in this study. Visualizations of the data from complex noise-exposed workers indicate that kurtosis may affect hearing threshold levels across frequencies ranging from 0.5 to 8 kHz, with the greatest effect at 4 kHz. The quantitative data analysis reveals that for workers exposed to noise levels between 80 and 92 dBA, without kurtosis adjustment leads to an underestimation of the risk of hearing loss, potentially excluding at-risk workers from the hearing conservation programs. Using kurtosis to adjust noise exposure levels is essential to identify those at risk of hearing loss and enroll them in hearing conservation programs. For noise exposure levels of 93 dBA or higher, further investigation is needed to determine the extent to which kurtosis influences hearing loss.

Further analysis for workers exposed to noise levels between 70 and 79 dBA could not be supported by the current data. Different noise kurtosis coefficients are obtained when using different dependent and independent variables, ranging from 6.1 to 7.9. However, none of these coefficients provides a perfect estimation of NIPTs, particularly at frequencies of 2 kHz or below.

In conclusion, the primary results of this study suggest that kurtosis plays a significant role in hearing loss when workers are exposed to average noise levels of 85 and 90 dBA (i.e., NIOSH REL and OSHA PEL, respectively). This highlights the importance of considering the enrollment process for complex noise-exposed workers into hearing conservation programs. Risk assessment analyses could help further examine the excess risk of hearing loss using kurtosis as a predictor when workers are exposed to complex noise. In addition, more data for noise exposure levels ranging from 70 to 79 dBA would be beneficial to enhance understanding within this range.

Author Contributions

Wei Gong designed and analyzed data and wrote the manuscript. Dr. David C. Byrne designed and supervised the project, and edited the manuscript. Christa L. Themann reviewed the data analysis methods and edited the manuscript. H. Amy Feng analyzed the data. All authors discussed the results and implications and commented on the manuscript at all stages.

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Disclosure

The findings and conclusions in this presentation are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), the Centers for Disease Control and Prevention (CDC).

Ethics Statement

The study protocol was approved by the Ethics Committee of Zhejiang and Jiangsu Province Centers for Disease Control and Prevention (approval reference number: ZJCDC-T-043-R and JSCDCCLL-2017-025).

Conflicts of Interest

The authors declare no conflicts of interest.

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