Evaluating worker noise exposure levels in the presence of complex noise

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ABSTRACT

Recent research into the assessment of worker noise exposure has demonstrated that the combination of impulsive noise and continuous noise creates an additional risk of developing noise-induced hearing loss (NIHL). Zhang et al. (2021) demonstrated that workers exposed to non-Gaussian noise accumulated NIHL at a faster rate over their careers than workers exposed to Gaussian noise. The kurtosis statistic of the sound pressure distribution provides a means to adjust the estimated risk of hearing loss between exposure groups exposed to different types of noise. This paper will review the results from our recent studies of kurtosis and exposure level. Some unanswered questions involve the selection of a suitable sample length to estimate kurtosis (Tian et al. 2021), the selection of an applicable compensation factor (Qiu et al. 2021), and understanding the differences exhibited in short (less than 10 years) and long-term exposures and kurtosis (Zhang et al. 2021).

1. INTRODUCTION

According to the National Occupational Research Agenda for Hearing Loss Prevention [1], noise exposure occurs across a broad range of industrial sectors (e.g. mining, construction, manufacturing, oil and gas extraction, and public safety). Noise exposures in different industries have different characteristics. For instance, construction noise may be more intermittent. Heavy equipment operators may experience essentially continuous exposures whereas framing carpenters may experience impulsive noise due to pneumatic nail guns. In manufacturing environments the noise exposures may be a continuous din that rarely changes in level or spectrum. In public safety and the military, high-level impulse noise from firearms can present exposure levels of 140 dB peak sound pressure level (pSPL) to 190 dB pSPL for shoulder-fired weapons or large-caliber howitzers [2]. The

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level and duration of a noise exposure are two factors that affect the risk of developing noise-induced hearing loss (NIHL).

Complex noises consist of impulsive noise embedded in a continuous background noise exposure. Impulsive noise can be defined as either impact noise (objects colliding) or impulse noise produced by combustion of gases (blast or shock waves). Several features of impulsive noise that affect the associated hearing loss are the duration of the impulse, the amplitude, and the inter-peak interval [3]. Hamernik and colleagues [4] conducted a series of noise exposure studies using chinchillas to investigate the relationships of complex noise exposures with changes in hearing and hair cell loss. These studies varied the level and the impulsive content of the exposures and demonstrated that the kurtosis metric could help to organize the outcomes of the exposures.

Lei et al. [5] proposed using kurtosis,

$$\beta = \frac{E[(x-\mu)^4]}{(E[(x-\mu)^2])^2}, \tag{1}$$

to characterize noise exposures. In evaluating workers' noise exposures, Zhao et al. [6] used cumulative noise exposure to reconcile impulsive and non-impulsive exposures,

$$\text{CNE} = L_{Aeq,8h} + K[\log T / \log 2] \tag{2}$$

where T is the exposure duration in years, $K = \ln(\beta) + 1.9$, and β is the kurtosis. This form worked well when the exposures were long term, but it is time-dependent and may not be particularly useful when analyzing exposure recordings that last only seconds. Goley et al. [7] proposed a kurtosis correction to the equivalent noise level that was not dependent upon the length of a person's exposure time,

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

where $\lambda = 4.02$, β is the kurtosis of the noise sample, and $\beta_G = 3$ is the kurtosis of a normal distribution.

In the development of a damage risk criterion for complex noise, kurtosis analysis has been proposed and the methods of determining a kurtosis value from a noise recording and how it can best be applied to estimate the risk are unanswered questions. Kurtosis is dependent upon the time window from which it is determined. The additional risk is not necessarily the same as the risk determined from animal experiments. The effect on hearing is also dependent upon the duration of noise exposures over the course of a worker's career. ISO 1999 estimates that within the first ten years of noise exposure, hearing loss accrues at a more rapid rate. [14] Complex noise may be expected to follow a similar pattern over the initial years of exposure. This paper will review the results from chinchilla noise exposures and present new findings that have been reported in a series of papers from full-shift noise recordings and audiometric evaluations of a large cohort of factory workers from the Zhejiang and Jiangsu provinces in the People's Republic of China. [9–11]

2. ANIMAL NOISE EXPOSURES

Impulse noise was known to present a greater risk of inducing noise-induced hearing loss. Dunn et al. [8] exposed chinchillas to either continuous or a comparable impulsive noise. The impulsive noise was 32,000 impulses of a hammer strike with a 120 dB peak level. The continuous noise was matched to the spectrum and equivalent level L_{eq} = 100 dB of the impulsive noise for four hours per day for five days. The permanent threshold shifts of auditory evoked potentials measured for the impulse noise-exposed animals were between 20 and 40 dB more than the continuous noise-exposed animals.

Qiu et al. [4] reported a series of complex noise exposures of chinchillas to 97 dB. The animals were exposed to noises that were either 24 hours per day for either 8 hours per day, for 5 or 19 days

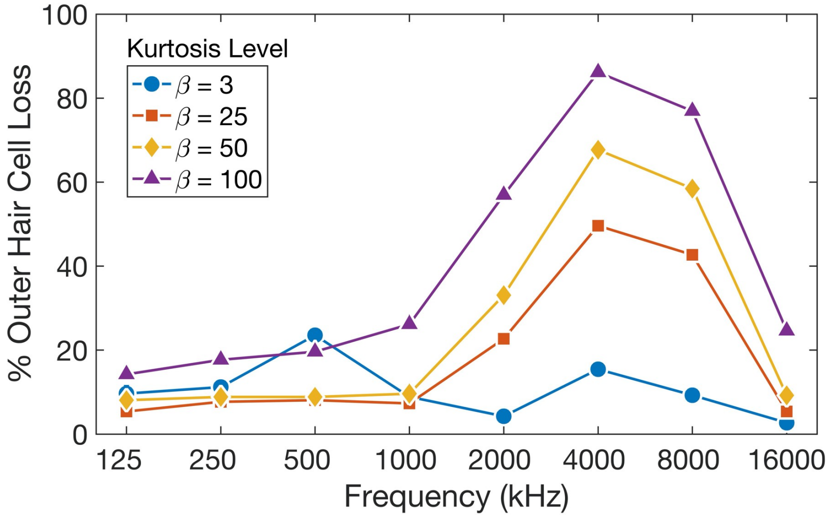

Figure 1: The average percent outer hair cell loss of three groups exposed to 97 dB SPL non-Gaussian noise with different kurtosis levels (β = 25, 50, or 100). The mean data from the group exposed to the 97 dB SPL Gaussian (β = 3) noise is shown for comparison. Adapted from Qiu et al. [4].

at 97 dB SPL. The groups were divided into Gaussian continuous noise exposures of 97 dB SPL, and non-Gaussian groups with kurtosis of 25, 50 or 100 with a variety of inter-peak intervals, peak levels, and durations. Qiu et al. [4] used a 40 second time window to analyze kurtosis in the animal studies. In Figure 1, the results for each of these exposure groups are summarized. One of the conclusions from this study and previous studies is that kurtosis provides an organizing principle for noises with different kurtosis values within the same exposure levels.

3. HUMAN NOISE EXPOSURES

The human data considered in this paper were drawn from a long-term cross-sectional study conducted in Zhejiang and Jiangsu provinces in eastern China. This study protocol was approved by the Ethics Committee of Zhejiang and Jiangsu Provincial Center for Disease Control and Prevention (approval reference number: ZJCDC-T-043-R and JSCDCLL-2017-025). Over the course of the study, different analyses of the data have been reported in several peer-reviewed manuscripts. These articles were written sequentially. Zhang et al. [9] was written in 2019 and accepted for publication in 2020. Tian et al. [10] was written in 2020 and accepted for publication in 2021. Qiu et al. [11] presents unpublished findings from an 2020 analysis that was motivated from discussions amongst the authors. It is anticipated that the article will be submitted and accepted for publication in 2021. This paper will present a summary of these three manuscripts. [9–11]

Full-shift recordings of the workers' exposures were captured by the AIHUA ASV5910-R digital noise recorder with a 6.35 mm microphone capable of recording from 40 to 141 dB SPL. The 48-kHz, 32-bit resolution recordings were stored on SD-micro cards. A fully-charged recorder could capture an entire 8-hour work shift. The noise recorder was mounted on the worker's shoulder with the microphone mounted midway between the shoulder and neck, a standard placement for the dosimeter microphone. Most of the factories had 8-hour work shifts. Noise recordings were collected from 4,916 workers from 34 factories over the period 2010 to 2018. Among them, 3,244 were noise-exposed workers, and 1,672 were non-noise-exposed employees, respectively. The peak levels of the noise exposures did not exceed the capacity of the microphones.

3.1. Kurtosis Level and Exposure Duration

Zhao et al. [6] demonstrated that the kurtosis-adjusted cumulative noise exposure metric (see Equation 2) better described the accumulation of noise induced permanent threshold shifts with the cohort of 192 subjects. Subsequent papers applied the cumulative noise exposure as the number of workers in the cohort increased. In Figure 2, the histograms of the Chinese workers' ages, durations of employment, noise exposure levels, and the kurtosis of the noise samples are displayed in panels A thru D, respectively. [9] The distribution of workers' ages were between 16 and 65 years old with a mode 35 years old. The duration of employment at the facilities ranged between less than a year to 35 years. The A-weighted noise exposure levels considered in the study ranged between L_{Aeq} = 85 and 100 dBA and had a mode of 88 dBA. The kurtosis of the noise samples were binned into four groups: $3 \leq \beta \leq 10$, $10 < \beta \leq 30$, $30 < \beta \leq 75$, and $75 < \beta$. Kurtosis was calculated for the noise samples by analyzing 40-second non-overlapping windows for each worker's full-shift noise recording. The mean of the kurtosis for all sample windows was used as the surrogate for the kurtosis of the worker's exposure over the work shift.

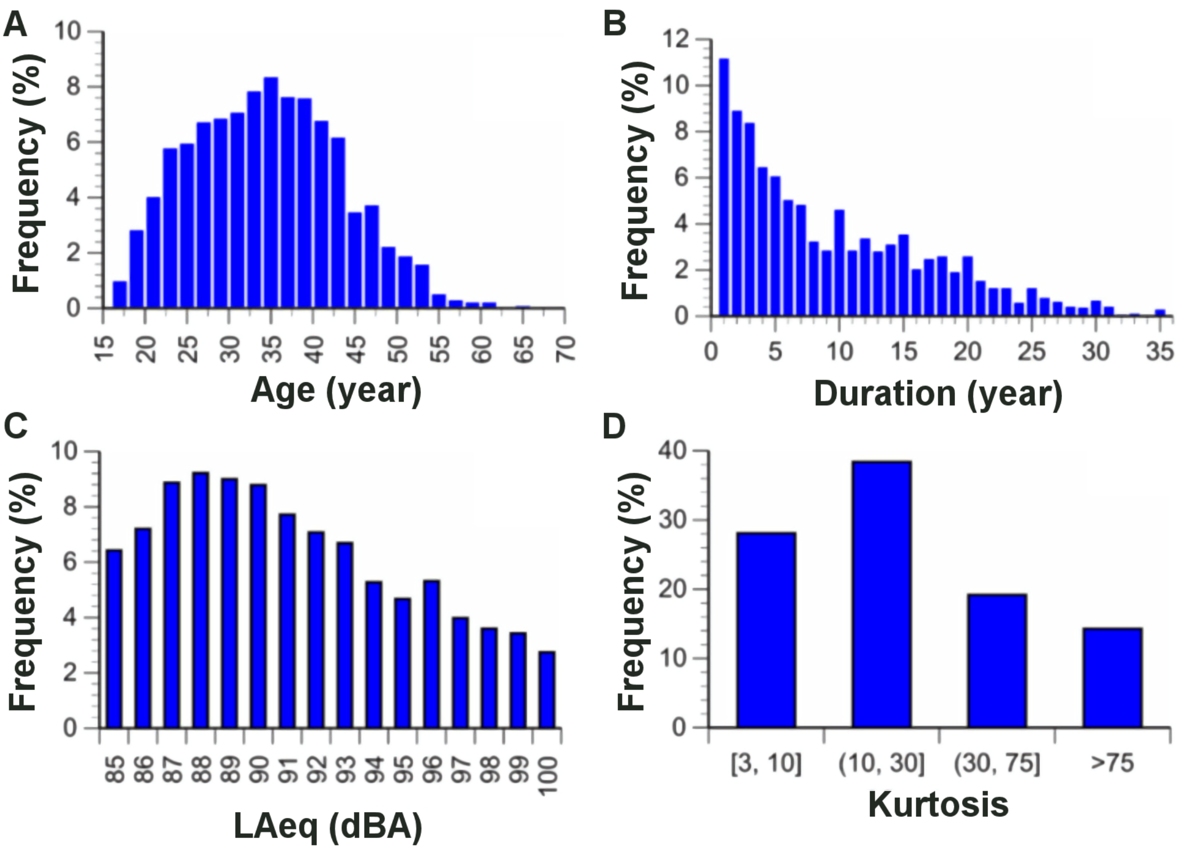

Figure 2: Distributions of (A) age; (B) exposure duration; (C) A-weighted equivalent sound pressure levels (L_{Aeq8h}); and (D) kurtosis values of the 2,333 noise-exposed workers. Adapted from Zhang et al. [9].

For workers with less than 10 years of employment in Figure 3, the shift in the pure-tone average over the frequencies 2, 3, 4, and 6 kHz (noise-induced permanent threshold shifts or NIPTS) exhibited a consistent rank ordering across the range of levels 85 to 88, 88 to 91, 91 to 94, and 94 to 100 dB. [9] The noise exposures with lower kurtosis exhibited less NIPTS. Higher noise exposures in noise level category 4, tended to lead to more hearing loss. For workers with more than 10 years of exposure, the effect of kurtosis seemed to be less significant. For noise levels L_2, L_3 and L_4, the three lowest kurtosis values overlap considerably and the differences were not statistically significant. The highest kurtosis category, $\beta > 75$, exhibited significantly more hearing loss across all noise categories. The error bars represent the standard errors of the NIPTS.

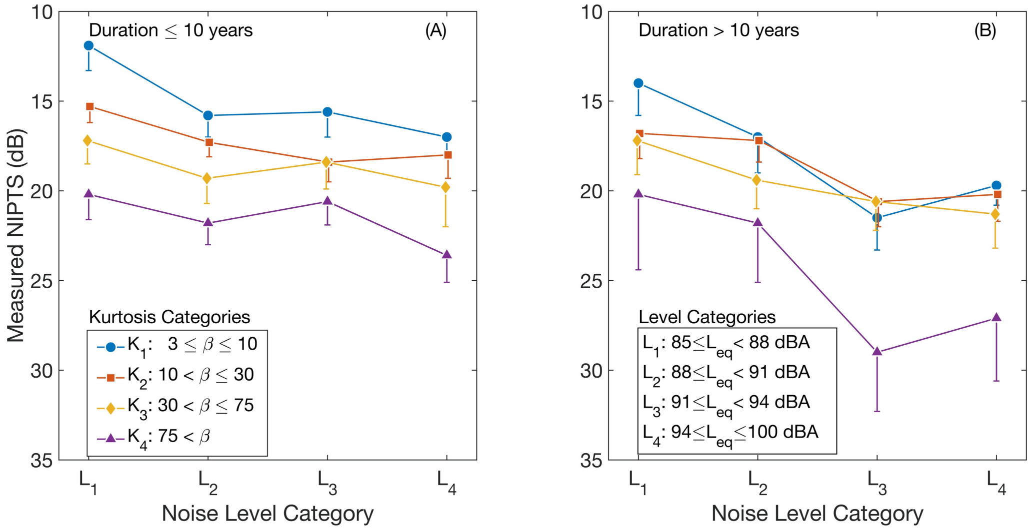

Figure 3: Noise-induced permanent threshold shifts measured for the Chinese workers separated by duration of employment ($D \leq 10$ years and $D > 10$ years), noise exposure levels ($85 \leq L_{eq} < 88, 88 \leq L_{eq} < 91, 91 \leq L_{eq} < 94$, and $94 \leq L_{eq} < 100$), and by kurtosis categories ($3 \leq \beta \leq 10$, $10 < \beta \leq 30$, $30 < \beta \leq 75$, and $75 < \beta$). Adapted from Zhang et al. [9].

3.2. Kurtosis Analysis Window Length

The kurtosis of an arbitrary noise sample is dependent upon not just the probability of a high-amplitude event occurring within the sample window, but also the length of the sample window. According to Müller [12], if the sample window contained one impulsive event yielding a kurtosis of β, then appending a window of the same length but filled with zeroes will double the kurtosis estimate, 2β. Kurtosis is also dependent upon the frequency content or filtering applied to the signal. Murphy [13] examined the varied effects of hearing protection devices upon the kurtosis of the noise signal that is transmitted through the protector. Earmuffs reduced kurtosis more than foam earplugs. The mechanism of kurtosis reduction has not been investigated carefully for noise exposures and hearing protection.

Two algorithms were tested against the data from the Chinese worker study to investigate the correlation between window lengths used to analyze kurtosis and the accuracy of the NIHL predictions. The first algorithm was a statistical test using the Mann-Whitney U test to compare the Cohen's d values when evaluating the differences between the low ($\beta < 50$) and high ($\beta \geq 50$) kurtosis groups in Hearing Threshold Levels (HTLs) between groups of data analyzed with fourteen different sample lengths ranging from 10 seconds to the entire work shift recording (8 or more hours). The second approach applied a support vector machine (SVM) and evaluated the area under the curve (AUC) for predicting NIHL (see Figure 4). Hearing loss threshold shifts were estimated by using either the average change across 1, 2, 3, and 4 kHz (HTL_{1234}) or across, 3, 4, and 6 kHz (HTL_{346}). The combined results of the Mann-Whitney test and SVM evaluation identified that the 60-s window was an optimal window duration for kurtosis calculation that allows for both efficient computation and high accuracy of the NIHL evaluation. In previous animal and human evaluations, the noise samples were analyzed with non-overlapping 40-s windows as determined from Lei et al. [5].

In Figure 4, the results of the SVM analysis of the predictive performance of average hearing threshold levels at 1, 2, 3, and 4 kHz (HTL_{1234}) and 3, 4, and 6 kHz HTL_{346}) are presented. The AUCs

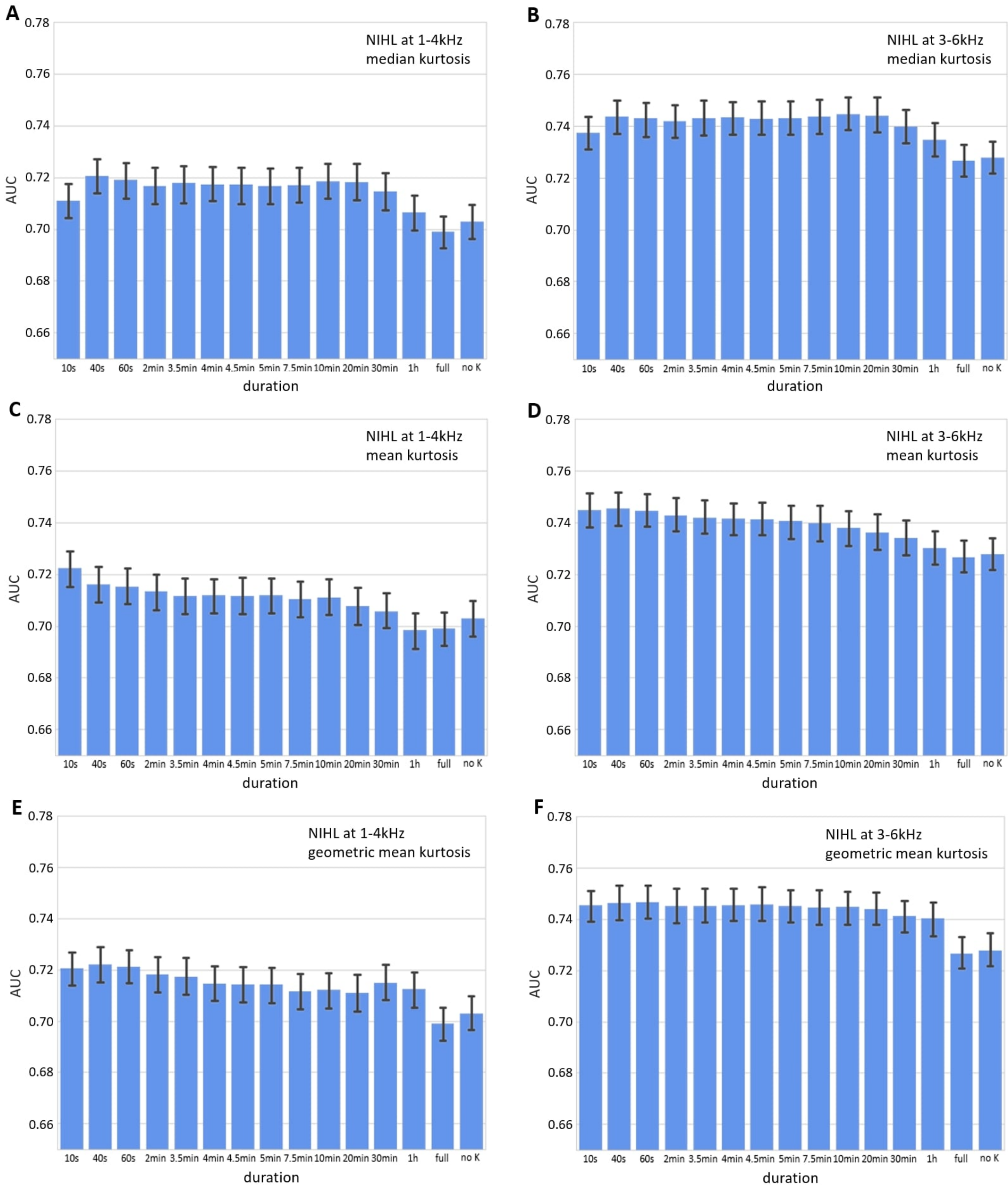

Figure 4: The area under the curve (AUCs) of the SVM models for NIHL prediction with kurtosis computed over different window durations. (A) models for average HTLs at 1, 2, 3, and 4 kHz (HTL_{1234}) and median kurtosis; (B) models for average HTLs at 3, 4, and 6 kHz (HTL_{1234}) and median kurtosis; (C) models for HTL_{1234} and mean kurtosis; (D) models for HTL_{346} and mean kurtosis; (E) models for HTL_{1234} and geometric mean kurtosis; (F) models for HTL_{346} and geometric mean kurtosis. Figure adapted from Tian et al. [10].

are represented by the bars for several approaches of estimating kurtosis for the samples of full-shift noise with different length windows. For most of the windows, the error bars do not indicate that the window lengths with the highest AUC are significantly better choices. However, window lengths of

1 hour and full-shift yielded the lowest AUCs for HTL_{1234} and HTL_{346}.

In Table 1, the window durations with the highest scores for the different algorithms, indicator of NIHL, and approach to estimating the overall kurtosis of the sample from a worker are presented (β_{Median}, $\beta_{\text{ArithmeticMean}}$, and $\beta_{\text{GeometricMean}}$). The 60-s window appears in the top three positions for 9 out of the 12 approaches, the 40-s window is in the top three positions for 7 out of 12 times. This finding suggests that the 60-s window is perhaps the better choice of the several possible window lengths and indicators of NIHL, (HTL_{1234} and HTL_{346}). These analyses were completed after the Zhang et al paper [9] was accepted for publication.

Table 1: The top three window durations for each algorithm for average hearing threshold levels at 1, 2, 3, and 4 kHz (HTL_{1234}) and 3, 4, and 6 kHz (HTL_{346}). The top three selections for algorithm 1 (Mann-Whitney U test) were obtained by selecting the three largest Cohen's *d* values at HTL_{1234} and HTL_{346}; the top three selections for algorithm 2 (support vector machine) were obtained by selecting the three largest areas under curves (AUCs) from the support vector machine (SVM) prediction models at HTL_{1234} and HTL_{346}. Table from Tian et al. [10]

	median	**mean**	**geometric mean**
Algorithm 1 at HTL_{1234}	2 min, 40 s, 60 s	2 min, 7.5 min, 10 min	2 min, 3.5 min, 60 s
Algorithm 1 at HTL_{346}	40 s, 5 min, 1 h	2 min, 3.5 min, 60 s	60 s, 5 min, 3.5 min
Algorithm 2 at HTL_{1234}	40 s, 60 s, 10 min	10 s, 40 s, 60 s	40 s, 60 s, 10 s
Algorithm 2 at HTL_{346}	10 min, 20 min, 7.5 min	40 s, 10 s, 60 s	60 s, 40 s, 10 s

3.3. Kurtosis Weighting Factor

When applied to short duration noise samples (e.g. a minute or less), the kurtosis-adjusted cumulative noise exposure metric yields significant reductions in the adjusted exposure level, as much as 40 or more dB. Goley et al. [7] proposed an alternative method to incorporate kurtosis in the analysis of complex noise (see Eq. 3), where the value for $\lambda = 4.02$ was derived from an analysis of chinchilla noise-exposure data. Goley's metric depends on the length of the sample window used to estimate kurtosis. In determining the dose of a noise exposure, distinct tasks can be accounted for through a ratio of the actual exposure duration and the permissible exposure time,

$$D = (C_1/T_1 + C_2/T_2 + ... + C_n/T_n) \times 100 \quad (4)$$

where

$$C_n = \text{total time of exposure at a specified level, and}$$
$$T_n = \text{exposure for which noise at this level becomes hazardous.}$$

This form can then convert the dose into an 8-hr TWA according to the following formula

$$\text{TWA} = 10 \times \log(D/100) + 85. \quad (5)$$

The chinchilla noise-exposure outcomes differ from those observed in humans - chinchillas tend to be more susceptible developing NIHL following noise exposures. In Qiu et al. [11], the Goley formula was evaluated against the Chinese worker data. The noise-induced permanent threshold shifts were determined for $NIPTS_{346}$ and evaluated with a regression model,

$$\text{Model 1} : \text{NIPTS}_{346} = b_0 + b_1 L_{\text{Aeq,8hr}} \quad (6)$$
$$\text{Model 2} : \text{NIPTS}_{346} = b_0 + b_1 L_{\text{Aeq,8hr}} + b_2 \log_{10}(\beta_N/3) + \epsilon \quad (7)$$

where the value of $\lambda = b_2/b_1$ and minimizes ϵ. The model was validated by comparing the difference between the actual $NIPTS_{346}$ and the estimated $NIPTS_{346}$ with or without kurtosis adjustment using the ISO 1999:2013 formulation [14]. The best fit for the kurtosis adjustment was $\lambda = 6.50$.

Table 2: Regression model results using $L_{\text{Aeq,8hr}}$ and kurtosis-adjusted $L_{\text{Aeq,8hr}}$ to estimate $NIPTS_{346}$.

	Coefficients B	λ (b_2/b_1)	t Stat	p-value	B Lower 95%	B Upper 95%
Model 1		NA			$R^2 = 0.75$	F = 182.20
Intercept	-36.25		-10.02	< 0.0001	-43.30	-29.02
$L_{\text{Aeq,8h}}$	0.57		13.50	< 0.0001	0.49	0.66
Model 2		6.50			$R^2 = 0.88$	F = 225.81
$L_{\text{Aeq,8h}}$	0.56		19.31	< 0.0001	0.50	0.62
$\log_{10}(\beta_N/3)$	3.64		8.22	< 0.0001	2.79	4.40

The Estimated Marginal Means (EMM) of the $NIPTS_{346}$ were compared of the unadjusted and kurtosis-adjusted $NIPTS_{346}$ for three different kurtosis categories from the data: $K_1, 3 \leq \beta_N \leq 10$; $K_2, 10 < \beta_N \leq 50$; and $K_3, \beta_N > 50$. In Figure 5, the EMMs of the $NIPTS_{346}$ for the unadjusted data increased (become less accurate) as the kurtosis level increased from categories K_1 to K_3. In contrast, the EMMs for the kurtosis-adjusted $NIPTS_{346}$ decreased slightly as the amount of kurtosis increased. The error in the estimate for the kurtosis-adjusted case was significantly less than that observed for the unadjusted case.

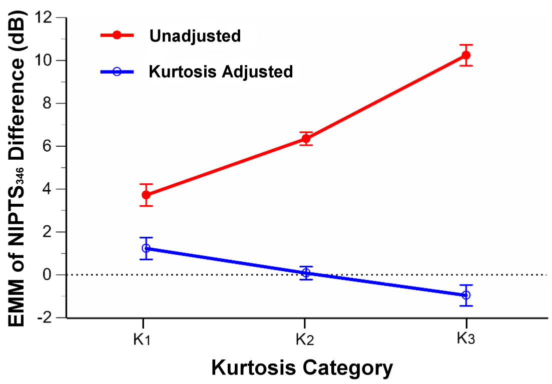

Figure 5: The EMM of underestimated $NIPTS_{346}$ by ISO 1999 model for three kurtosis levels under unadjusted and kurtosis-adjusted noise levels. Error bars: standard error. Adapted from Qiu et al. [11].

4. DISCUSSION

The analysis of complex noise is an important problem that has been reviewed. Zhao et al. [6] demonstrated with a small cohort of workers that non-Gaussian noise could be reconciled with the workers exposed to Gaussian noise. That study and those that followed added more evidence to the utility of considering kurtosis as a means of adjusting the noise exposure to account for the increased risk of NIHL. The chinchilla noise exposure studies demonstrated that the kurtosis adjustments have limits. For noise levels below about 75 dB, kurtosis did not have a strong effect on hearing loss in the animal models. For exposure levels $L_{eq} \geq 90$ dBA and kurtosis values $\beta \leq 50$, hearing loss observed in chinchillas produced a higher prevalence as kurtosis values increased. Above kurtosis values of about $\beta = 50$, the risk of hearing loss plateaued. For noise exposure levels higher than 95 dBA, the risk tended to exhibit more rapid growth at lower kurtosis levels and the plateau seemed to occur earlier. Likewise for lower noise exposure levels, the risk accelerated more slowly and the plateau occurred at higher values of kurtosis. The final kurtosis adjustment may require a variable to adjust for level. With noises below 75 dB SPL, the kurtosis adjustments should be very small or nothing at all. For high noise levels, the plateau region may require an asymptote that limits the kurtosis adjustment. [4]

Additional limits on the applicability of kurtosis adjustment may be necessary when evaluating high-level firearm noise or other impulses. The Chinese worker data do not include levels above 140 dB pSPL. Extensive animal noise exposures have been conducted but are not discussed here. Different loss mechanisms may be involved for high-level exposures. Other researchers have noted that very high levels can result in immediate mechanical trauma to the cochlea following exposures to weapon noise, whereas industrial noise exposures are more likely to involve metabolic exhaustion and damage to the stereocilia of the outer hair cells. [15, 16]

In Zhang et al. [9], for workers with fewer than 10 years of employment, the different noise categories ($L_1 - L_4$) exhibited increased risk of hearing loss as the noise level increased. As well, the different levels of kurtosis yielded distinct exposure groups with respect to the NIPTS that were measured. However, for workers with more than 10 years of employment, the first three kurtosis groups seem to have collapsed upon one another while the highest level kurtosis group was separated and exhibited more hearing loss.

From Goley's study of kurtosis with chinchilla [7], the functional form used by Zhao et al. [6] Eq. 2 was simplified into the form in Eq. 3. The kurtosis-adjustment factor that Goley derived was $\lambda = 4.02$. Qiu's analysis has considered other possible values and found that $\lambda = 6.50$ yielded a better prediction of the NIPTS at 3, 4, and 6 kHz in the noise-exposed workers. Since this value was derived from the human data, it might be a better choice for future analysis of complex noise exposures.

In the calculation of kurtosis, the time window has a significant effect on the outcome. After considering a range of sample window lengths, Tian et al. [10] found that 60 seconds provided an optimal length with regards to the predictions of NIPTS. This length is close to the 40 second window that previous analyses had used. Tian et al. and others have analyzed kurtosis using the entire sample over the window, but there may be reasons to consider the kurtosis for fractional octave bands. Murphy [13] found that the filtering effect of hearing protectors affected the kurtosis adjustments by as much as 3 to 6 dB. Since the work in China included workers who were largely not using hearing protection before the studies, a future research question should include the analysis of noise exposures when the attenuation of hearing protection is known.

With regards to implementing kurtosis in a sound level meter or dosimeter, AIHUA has already included kurtosis adjustment into a version of their equipment. Kurtosis does not require a lot of computational resources. Adding kurtosis to consensus standards from ISO or ANSI may be the impetus for equipment manufacturers to include it as an option. Options that could be implemented are different window lengths for kurtosis, exponential weighting, fractional octave band analysis, or time constants like what are currently used in noise measurements.

5. CONCLUSIONS

The results from the Chinese worker studies have been fruitful. With the findings, a new revision of the ISO 1999 standard to estimate hearing loss due to noise exposure is being prepared. The inclusion of kurtosis is planned to be included as an informative note. As dosimeters, sound level meters, and analysis tools come to the commercial markets, more detailed measurements will hopefully provide confirmation of this approach to account for complex noise exposures in the workplace.

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DISCLAIMER

The findings and conclusions in this report are those of the author and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH, CDC.

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