Kurtosis: A New Tool for Noise Analysis

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Introduction

Hearing loss due to high-level noise exposure remains a significant occupational health hazard that continues to increase in prevalence in industrial and military work environments despite government-mandated hearing conservation programs. The underlying assumption in current noise standards is that hearing loss over an 8-hour A-weighted equivalent continuous exposure level (often abbreviated as $L_{Aeq,8h}$) can be predicted by the equal energy hypothesis. This method assumes equivalent effects on hearing for a 3 dB increase or decrease in exposure intensity with a halving or doubling of exposure duration, respectively. In other words, equal amounts of hearing loss are expected regardless of how the noise exposure levels have occurred over time. The equal energy hypothesis is the basis of most noise standards and guidelines in the United States and internationally. Although this approach is generally considered appropriate for steady-state noise, it is not adequate for complex noise (Hamernik and Qiu, 2001).

Some Background

Consensus has been lacking on the use of simple energy averaging to predict the effects of noise on hearing. In the United States, some government agencies use a modification consisting of a 5 dB trading relationship, whereas others use the internationally accepted 3 dB rule. Use of the 3 dB rule has been recommended by the National Institute of Occupational Safety and Health (NIOSH) since 1998, which recommendation has been validated based on additional, more recent research (Suter, 2017).

Another issue with using a simple energy metric is the inability of sound energy averaging to account for the increased hazard of noise with impulsive components. Although intermittences in noise exposures may have been considered helpful to hearing in the past, this no longer seems to be the case with complex noise exposures, which are found frequently in manufacturing industries. Because the additional hazards from impulsive noise were already recognized, the earliest version of the International Standards Organization (ISO) 1999 standard (1971) suggested a 10 dB adjustment to the average exposure level when impulsive noise is superimposed on a background of continuous noise. At a 1981 meeting of noise experts in Southampton, UK, some participants proposed keeping the 10 dB adjustment, with others wanting to change it to 5 dB, and a third group proposing just using simple energy averaging (Personal Observation, Suter, 1981). The resulting report concluded that hearing conservation programs should be initiated at a 5 dB lower level as a precautionary measure whenever there are impulsive noise conditions (von Gierke et al., 1981). Consequently, the 1990 version of the standard contained a note suggesting a 5 dB correction but even that disappeared without explanation in later iterations of the ISO 1999 standard (2013). Since then, more evidence has emerged regarding the hazard to hearing from complex noise environments relative to continuous noise environments.

Complex or Non-Gaussian Noise

A steady-state, continuous noise exposure typically has a normal or Gaussian amplitude distribution (see background in **Figure 1**). However, the temporal pattern of noise exposures often varies significantly in work environments. A complex noise environment may be described as Gaussian background noise punctuated by a series of high-level transient noises resulting in a non-Gaussian distribution (as shown in **Figure 1**). These transients can be brief, high-level noise bursts, impulses, or impacts with varying interpeak intervals, peak levels, and peak durations. Industrial workers are often exposed to complex noise environments. Examples include jobs involving maintenance work, metalworking, and power tools, such as impact wrenches and nail guns.

Over the past several decades, a number of studies using animal models have shown that exposure to complex noise produces more hearing damage than an equivalent energy

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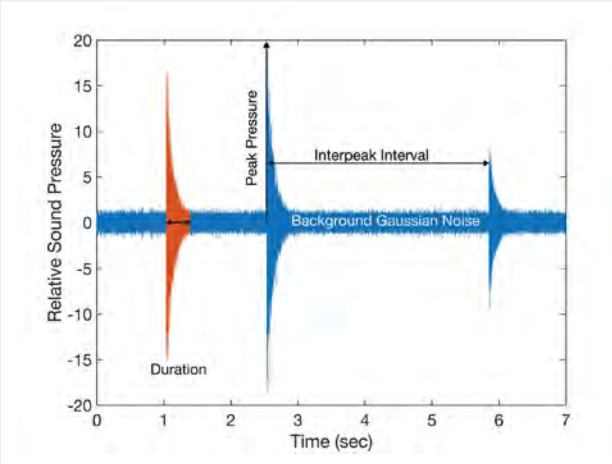


Figure 1. *An example of complex non-Gaussian noise.*

exposure to continuous Gaussian noise, in terms of both behavioral hearing loss and sensory cell loss (e.g., Lei et al., 1994). These results, along with similar findings from human data in industrial settings, have demonstrated that although acoustic energy and exposure duration are necessary metrics, they are not sufficient to evaluate the hearing loss from complex non-Gaussian noise exposure. Because many noise environments can be characterized by the same equivalent energy and spectra, a metric that describes the temporal structure of an exposure would be a useful adjunct to the equivalent sound pressure level metric. The kurtosis of a sample distribution is such a metric.

The Use of Kurtosis in Noise Analysis

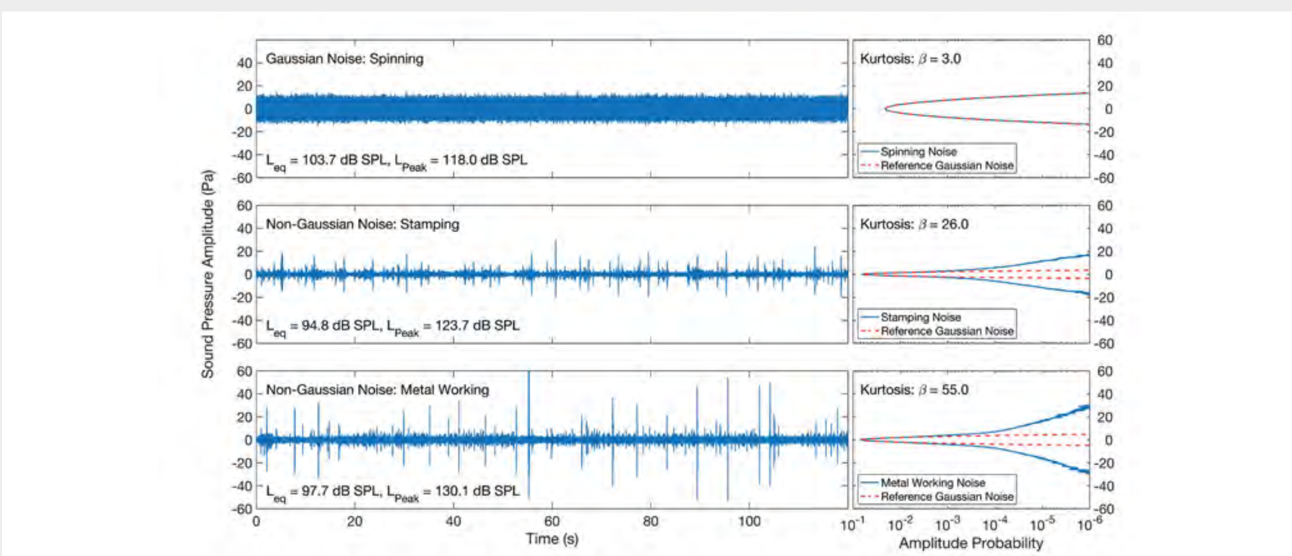
What is Kurtosis?

Kurtosis (β) is a statistical measure of extreme values (or outliers) in data in either tail relative to a Gaussian distribution. Datasets with high kurtosis values have more outliers, whereas datasets with low kurtosis have fewer outliers. Put another way, kurtosis is a measure of the amplitude "peakedness" of a noise waveform, with the impulsive components of complex noise as the outliers relative to a Gaussian noise. A Gaussian distribution, such as that shown in the panels of the top row of **Figure 2**, has a kurtosis of $\beta = 3$. These non-Gaussian transients may be impacts or noise bursts of varying peak intensities, with time intervals between noise bursts and impact durations, all of which are related to hearing damage.

The peak levels, interpeak intervals, and impact durations of the transients in the noise signal (see **Figure 1**) can be used to quantify the temporal structure of complex noise. Kurtosis accounts for all three of these temporal variables known to affect hearing loss in a single metric, making kurtosis a useful tool for noise analysis.

Figure 2, *left*, illustrates recordings from three industrial environments and their associated amplitude probability

Figure 2. *Comparison waveforms (**left**) and amplitude probabilities (**right**) from three industrial noises: spinning, stamping, and metal working.* ***Red lines****, background Gaussian noise probabilities.* L_{eq}*, equivalent sound exposure level; SPL, sound pressure level;* L_{peak}*, peak exposure level.*



histograms on a logarithmic scale (**Figure 2**, *right*): spinning ($\beta = 3$), stamping ($\beta = 26$), and metal working ($\beta = 55$). The amplitude probability histograms show the probability that a varying noise exposure exists at a specific amplitude value. The kurtosis of the recorded noise was computed over nonoverlapping consecutive 40-second time windows using a sampling rate of 48 kHz. The kurtosis value for each noise exposure was obtained using the mean of the measured kurtosis values. The waveforms in the panels on the right side of **Figure 2** show that the noise amplitude distributions with heavier tails have higher kurtosis values.

Researchers have shown that impulsive noise can cause more damage to hearing than steady-state noise (e.g., Taylor et al., 1984; Hamernik and Qiu, 2001). In an industrial noise environment, however, the definition of impulsive noise is often vague, and this affects the accuracy of any noise-induced hearing loss evaluation. Evaluating the hazards of impulsive noise then requires first designing a criterion to categorize the exposure as impulsive or nonimpulsive. To do this, Erdreich (1986) presented a distribution-based definition of impulsive noise and demonstrated that kurtosis was a sensitive discriminator of the impulsiveness of noise. The advantage of using kurtosis is that it accounts for the contribution of all peaks as well as the relative difference between peak and background levels. Although kurtosis was identified as a reasonable criterion for differentiating between impulsive and nonimpulsive noise, it still did not solve the problem of evaluating noise-induced hearing loss. Most industrial noises are complex, non-Gaussian noises with varying temporal structures that cannot be simply divided into impulsive and nonimpulsive noise.

Experiments Using Kurtosis

Over recent decades, much of the research in the area of noise-induced hearing loss has involved animal models, particularly the chinchilla, because its audibility curve and reactions to noise are similar to those of humans. Effects from these kinds of experiments are usually measured in terms of noise-related damage to the delicate microstructures, the ciliated cells, or cochlear outer hair cells of the inner ear.

Figure 3 shows differing levels of hearing loss due to noise exposures with the same spectra and energy but different temporal structures. In a series of experiments, four groups of chinchillas were exposed to noise with the same level (97 dB sound pressure level [SPL]) and spectra but with different temporal structures ($\beta = 3$, 25, 50, and 100, respectively). The results showed that for the same exposure level and spectra, the cochlear damage in terms of outer hair cell loss was greater in groups exposed to non-Gaussian noise ($\beta > 3$) than for the group exposed to Gaussian noise ($\beta = 3$), and hearing loss increased with kurtosis.

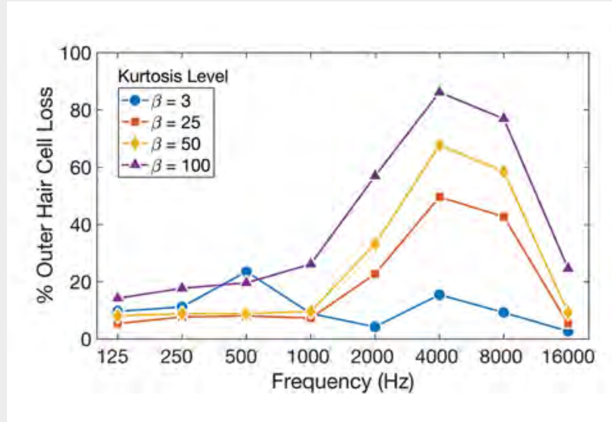


Figure 3. *The average percent outer hair cell loss of three groups exposed to 97 dB SPL non-Gaussian noise with kurtosis (β) = 25, 50, or 100. The mean data from the group exposed to the 97 dB SPL Gaussian (β = 3) noise is shown for comparison. Adapted from Qiu et al., 2013.*

Kurtosis as a Metric in Noise Analysis

The results in **Figure 3** indicate that kurtosis can be an important factor in the assessment of noise-induced hearing loss. However, the following questions needed to be resolved for kurtosis to be used as an adjunct to energy in the prediction of hearing hazard from both Gaussian and non-Gaussian noise exposures. First, is hearing loss monotonically related to the value of kurtosis? And next, is hearing loss independent of the detailed temporal structure of the complex noise?

The first question was addressed through four separate chinchilla experiments using the same overall noise exposure level (e.g., Lei et al., 1994; Hamernik et al., 2007). **Figure 4**, which shows mean total outer hair cell loss as a function of increasing kurtosis at a noise exposure level of 100 dB(A), provides the answer. It is clear that these losses increase monotonically with increasing values of kurtosis in the range of 3 to 50, above which the hearing damage appears to plateau.

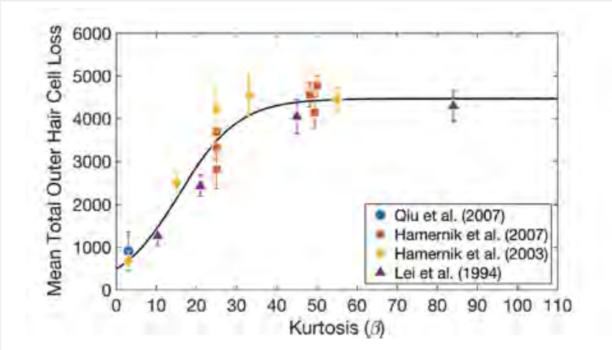


Figure 4. *The group mean total number of outer hair cells missing as a function of kurtosis in four separate studies using a noise exposure level of 100 dB(A). Adapted from Davis et al., 2009.*

The second question emerged because an infinite combination of amplitudes, peak durations, and interpeak intervals can yield the same kurtosis value. To answer it, Qiu et al. (2013) exposed chinchillas to noises with a variety of temporal distributions, including different peak levels, interpeak intervals, and peak durations. The results showed that the hearing losses were reasonably independent of temporal distributions as long as noise levels and kurtosis values were the same.

What Have We Learned About the Kurtosis Metric from Animal Experiments?

There are four key findings from this animal research (Hamernik et al., 2003; Qiu et al., 2013):

(1) Non-Gaussian noise is more hazardous than Gaussian noise equivalent energy, and kurtosis explains much of the increase.

(2) Hearing loss is proportional to kurtosis in that threshold shift and hearing loss increase as kurtosis increases for a fixed energy level.

(3) Both energy and kurtosis are necessary to assess the risk of hearing loss caused by a complex noise exposure.

(4) For fixed values of kurtosis and energy, the detailed temporal structure of an exposure does not have an appreciable effect on hearing loss.

This body of animal data needed to be correlated with comparable human noise exposure and audiometric data. Specifically, real industrial noise environments needed to be analyzed to measure their statistical and temporal properties and to quantify them in a form (e.g., kurtosis) that could be correlated with hearing thresholds of noise-exposed workers.

Examining the Effects of Kurtosis in Industrial Settings

A preliminary study of the use of kurtosis with a cohort of Chinese industrial workers (Zhao et al., 2010) showed that the kurtosis metric could increase the accuracy of assessing the risk of high-frequency hearing loss in workers exposed to high levels of both Gaussian and non-Gaussian noise. This study utilized a new approach to characterize the hazardous effects of complex noise in which an energy-based metric, cumulative noise exposure, was combined with a kurtosis-related correction term.

To incorporate the kurtosis metric into the evaluation of non-Gaussian noise environments and to unify the data from the two noise classes (i.e., Gaussian and non-Gaussian), Zhao and colleagues developed a kurtosis adjustment formula using Earshen's (1986) concept of cumulative noise exposure (CNE): CNE = $L_{Aeq,8h} + K$ [log T/log 2], where $L_{Aeq,8h}$ is the 8-hour A-weighted average exposure level, T is noise exposure duration in years, and $K = \ln(\beta) + 1.9$. By introducing the kurtosis variable (K) into the temporal component of the CNE calculation, the two dose-response curves were made to overlap, essentially yielding an equivalent noise-induced effect for the two study groups (see **Figure 5**). Thus, the kurtosis statistic was used to quantify the difference in effect between the Gaussian and non-Gaussian noise environments.

Xie et al. (2016) conducted a larger study of 178 subjects exposed to complex non-Gaussian noise from two steel plants and 163 subjects exposed to Gaussian noise from a textile plant. The results showed that for similar cumulative noise exposures, the complex noise caused significantly more hearing loss than the Gaussian noise. By using the same kurtosis-adjusted cumulative noise exposure measure as before, the hearing loss curves from the complex noise and Gaussian noise overlapped once again. These results supported the results from Zhao et al. (2010).

The above studies lead to two important conclusions. First, the diversity of complex noise environments over many industries make it difficult to characterize the expected hearing loss with a single dose-response curve. Nevertheless, the relative stability of the relationship between hearing loss and continuous Gaussian noise may serve as a reference to compare with the results from a complex noise exposure. Second, the kurtosis statistic appears to be a reasonable candidate for modifying

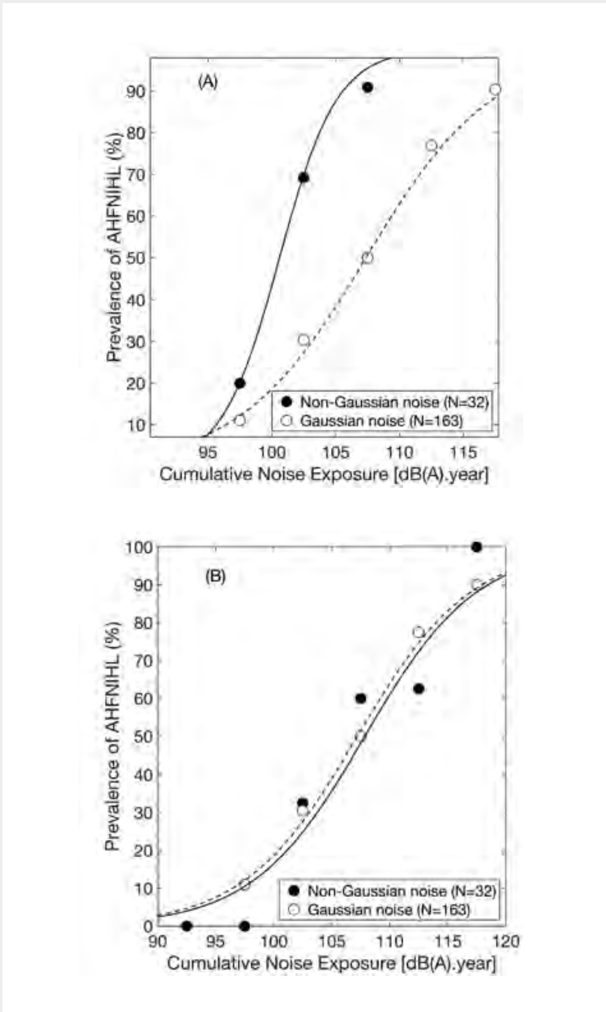


Figure 5. *Prevalence of age-adjusted high-frequency hearing loss (AHFNIHL) as a function of cumulative noise exposure for workers exposed to Gaussian versus complex (non-Gaussian) noise.* ***A:*** *unadjusted dose-response curves.* ***B:*** *kurtosis-adjusted dose-response curves. Adapted from Zhao et al., 2010.*

exposure level calculations to estimate the risk of hearing loss from any type of noise environment. Kurtosis can be used to adjust the cumulative noise exposure to yield a consistent estimate of hearing loss from exposures across a variety of noise environments using a single metric.

Recently, Zhang and colleagues (2020) conducted large-scale (N = 2,333) epidemiological studies in Chinese industries. To evaluate the effects of noise level, duration, and kurtosis on hearing loss, the entire cohort was divided into four noise-exposure levels, two exposure durations, and four kurtosis categories. The details of these divisions are presented in **Figure 6**.

Figure 6 shows the effects of noise level and kurtosis on the actual measured noise-induced threshold shift for these two exposure durations: less than 10 years and greater than 10 years. The results from this database of workers exposed to various industrial noises are in general agreement with previous experiments using the chinchilla model.

Human data, however, show some peculiarities.

(1) For exposure durations less than or equal to 10 years, the relationship between hearing loss and kurtosis value is clear. For a fixed noise level, noise-induced hearing loss increased as the kurtosis value of the noise increased (as shown in **Figure 6A**). In the first decade of exposure to high-level noise, complex noise with a kurtosis greater than 10 was more hazardous than steady-state Gaussian noise.

(2) As the exposure duration increased beyond 10 years, the difference in hearing loss between the Gaussian (K_1), low (K_2), and medium (K_3) kurtosis groups ($\beta \leq 75$) tended to fade away (as shown in **Figure 6B**). However, the hearing loss in the high (K_4) kurtosis group ($\beta > 75$) was still significantly larger than that of other groups. This suggests that the presence of certain types of impulse or impact noise characterized by high kurtosis values can cause hearing damage faster and continue over a long exposure time.

Consistent with ISO 1999, hearing loss occurs more quickly during the first 10 years of exposure to complex noise environments, and these data demonstrate the necessity of attention to workers from the beginning of their noise exposures.

Some Considerations Regarding the Kurtosis Application

Kurtosis Calculations

For a sample of n values, the kurtosis is calculated as

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

where x_i is the ith value and $\bar{x}$ is the sample mean. If, based on existing data, one accepts the proposition that kurtosis should be routinely measured in all industrial noise exposures, then one must try to find the best way to measure it. Because the kurtosis value is dependent on the length of the window over

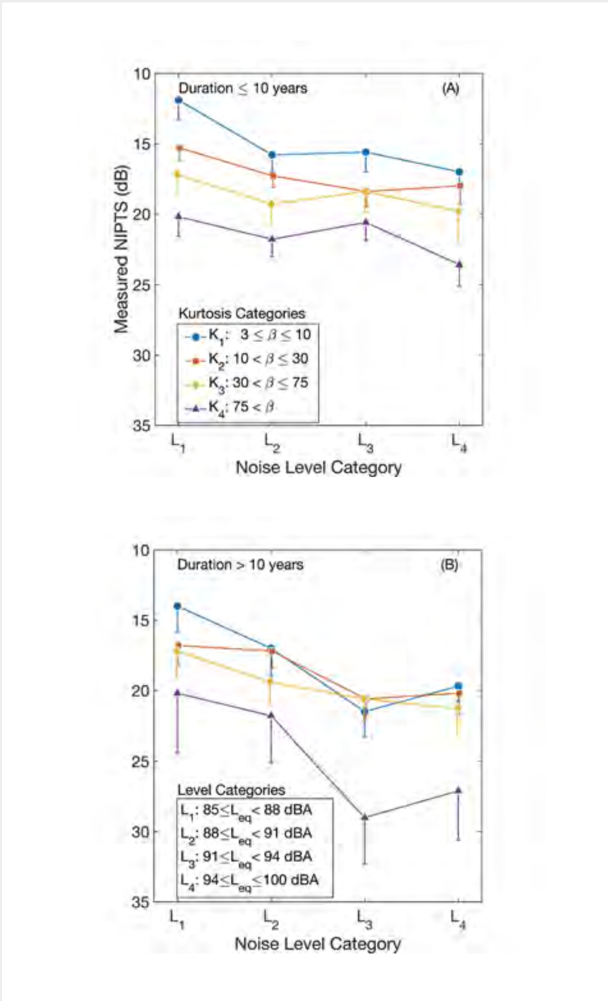


Figure 6. *The estimated marginal means of the actual measured noise-induced permanent threshold shift (NIPTS) at each kurtosis value across test frequencies for four noise-level bins in two different exposure durations:* ***A:*** *less than or equal to 10 years.* ***B:*** *greater than 10 years. Error bars, standard error of the means. Adapted from Zhang et al., 2020.*

which the calculation is made, its calculation is limited by the computer's processing capabilities. All previously cited human studies chose to use a 40-second time window based on the work of Hamernik et al. (2003). The mean of the measured kurtosis values was calculated and used as the kurtosis metric for a full-shift noise exposure.

Kurtosis as an Adjunct to Energy in the Evaluation of Noise-Induced Hearing Loss

Because noise-induced hearing loss is directly related to both noise level and exposure duration, increases in each parameter can be expected to increase the extent of hearing loss. As mentioned in the **Introduction**, a complex non-Gaussian noise is more harmful to hearing than a Gaussian noise with the same noise level and exposure duration. Additional hearing loss caused by complex noise is positively correlated with the kurtosis of noise. Thus, a proper kurtosis correction through an equivalent exposure level ($L_{Aeq,8h}$) or exposure duration may serve as a good noise metric for assessing the risk of noise with different temporal characteristics. So far, two kurtosis adjustment methods have been considered.

Method 1: Kurtosis Adjustment Through Exposure Time

This method was used in Zhao et al. (2010) and Xie et al. (2016) and was discussed in ***Kurtosis Calculations***. The adjustment formula is shown below

$$\mathrm{CNE}(\beta) = L_{Aeq,8h} + \frac{\ln(\beta)+1.9}{\log(2)}\log(T) \tag{2}$$

where T is exposure duration in years. It can be seen from Eq. 2 that for a fixed 8-hour exposure ($L_{Aeq,8h}$), the kurtosis adjusted CNE will be larger for non-Gaussian noise ($\beta > 3$) than for Gaussian noise ($\beta = 3$), which is equivalent to extending the duration of noise exposure, provided that the exposure time is greater than one year. The application of Zhao's method was introduced above and the results are shown in **Figure 5**.

Method 2: Kurtosis Adjustment Through Energy

Goley et al. (2011) presented another way to use kurtosis in the evaluation of hearing loss, which differed from the method proposed by Zhao et al. (2010). Instead of making the kurtosis correction through the exposure time, Goley et al. proposed a method that uses kurtosis to directly adjust the A-weighted equivalent sound pressure level (L_{Aeq}). The following kurtosis-correction formula was proposed

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

where λ is a positive constant determined from the dose-response correlation study, β is the kurtosis of the noise, and $\beta_G = 3$ is the kurtosis of the Gaussian noise. Using Goley et al. (2011) method is equivalent to adding a penalty, determined by the second term in the formula, to the overall sound pressure level. Goley and colleagues applied this model to Zhao et al.'s data (2010) and found similar results, as shown in **Figure 5B**.

The Goley et al. (2011) method provides an adjustment to the noise exposure that is independent of the sample duration. Assuming that the permissible exposure is an 8-hour A-weighted sound pressure level of 85 dB(A), the kurtosis correction would adjust the level and the potential contribution to the dose accordingly

$$D = 100*(C_1/T_1 + C_2/T_2 \ldots + C_N/T_N) \quad (4)$$

where the C_i values are the times at a given exposure level and the T_i are the permissible times for that same level

$$T_i = \frac{480}{2^{((L_i-85)/3)}} \quad (5)$$

If a worker were exposed to 91 dB with a kurtosis level of $\beta = 3$, the allowable time would be 2 hours (120 minutes) before a 100% dose would be reached (NIOSH, 1998). If the kurtosis for that same noise exposure level were 15, the kurtosis-adjusted noise level would be about 3 dB higher [$4.02*\log_{10}(15/3) = 2.81$], resulting in a reduction of exposure time by approximately 50%.

The Kurtosis Metric in Other Applications

Use of Kurtosis to Evaluate the Combined Effects of Noise and Solvent Exposures

Fuente et al. (2018) conducted a pilot study to test the possible interactive effects of noise and a mixture of chemical solvents that can cause hearing loss. They selected 20 workers exposed to noise plus a mixture of solvents (toluene, xylene, ethylbenzene, and styrene) and 20 exposed only to noise. Each worker was assessed for solvent exposure and for noise using the CNE and the kurtosis-adjusted CNE. Interactions between the noise exposure (unadjusted) and solvent exposure were not significant for the hearing thresholds 1,000 Hz through 8,000 Hz. There was, however, a significant effect at 6,000 Hz when the cumulative noise exposure was adjusted for kurtosis. This pilot study provides evidence that when noise is combined with certain solvents, the use of kurtosis may help identify a harmful effect.

The Effect of Hearing Protection Devices on Kurtosis

Currently, hearing protection devices are commonly used to protect workers from high-level noise exposures. The effects of hearing protection on kurtotic noise exposures is largely unknown. Murphy (2019) investigated the effect of hearing protection devices on the kurtosis of noise from a jackhammer (a pneumatic or electric chisel used to break up concrete) using an acoustic test fixture placed approximately two to three meters away from the operator. He evaluated hearing protector conditions, alternating between the ears-covered and ears-uncovered conditions as the jackhammer chiseled through a 6-inch-thick slab of 5,000 psi concrete. The ears-uncovered kurtosis of the jackhammer noise was 15, whereas the ears-covered conditions varied between 2.6 and 12.1 depending on the hearing protector. The earmuff condition reduced more of the high-frequency components of the noise than the low- and midfrequencies and yielded a kurtosis of about 2.6. One of the earplugs with a nonlinear filter yielded a kurtosis of 12.1 in the open-filter condition. The kurtosis adjustment to the noise level varied between −0.3 and +2.3 dB. The A-weighted attenuation of the protectors, however, varied between 21 and 41 dB. For this exposure, a properly fitted hearing protector had a greater effect on the allowable exposure time than the reduction in exposure time due to a high kurtosis level. Future efforts could include a better understanding of the interaction between kurtosis and the frequency characteristics of both the noise environment and the hearing protector attenuation.

Kurtosis in the Future

Kurtosis in Practice

Further research is needed to apply kurtosis to programs for the prevention of noise-induced hearing loss.

Establishment of Protocol for Kurtosis Application

The window length necessary for computing kurtosis and the sampling rate for noise recordings directly affects the kurtosis value of a noise. Therefore, in specific environments such as industrial settings, noise exposures can be clearly and effectively characterized by kurtosis only when the window length and the noise sampling rate are fixed or standardized. The choice of window duration should consider computation efficiency and accuracy to predict hearing damage, along with the choice of noise sampling rate. The effective range of human hearing is 20 to 20,000 kHz. A sampling rate of 48 kHz can cover the audible frequency range for humans and should be suitable for industrial noise sampling. However, military impulse-noise bursts are usually very short, and sampling rates of 200 kHz or above are often used for detailed analysis of these impulse noises. Therefore, it is necessary to develop a kurtosis analysis protocol according to the application situation, the type of noise (impulse or impact noise), effects of sampling rates, and filtering.

The effective range of kurtosis in hearing loss evaluation also needs to be determined because the effectiveness of kurtosis is related to exposure level. If the average energy level of the noise exposure is low (e.g., less than 70 dB), it will not contribute to hearing loss no matter how high the value of kurtosis is. At the other extreme, if the peak level of an impulse noise exceeds 140 dB SPL, the mechanisms of hearing damage include both mechanical (potentially immediate effects) and metabolic (longer term effects) strains. The use of kurtosis would be questionable because there are no data about its effectiveness in this area.

Development of Noise Measurement Equipment

The application of kurtosis in noise analysis requires determining the appropriate methods for incorporating kurtosis in a noise measurement. Subsequently, the firmware of noise measurement devices (sound level meters or dosimeters) and existing standards for noise measurement and equipment specifications (e.g., ISO 9612 and IEC 60804) will need to be updated to include kurtosis.

Kurtosis in Theory

Interpretations of the kurtosis statistic for the wide range of noise distributions encountered by acousticians have not been established. Three amplitude distributions may specifically apply to acoustics and kurtosis: (1) pure tones have a bimodal distribution with peaks at the maximum/minimum pressures; (2) white noise has a normal, Gaussian distribution; and (3) impulsive noise can be realized using a randomly occurring sequence of exponentially decaying noise (see **Figure 1**). Complex noise may contain pure tones, white noise, and impulsive noise. Quantifying the pure tones, white noise, and impulsive noise may be useful to develop a more realistic noise exposure model (Zechmann, 2019).

Conclusions

Noise-induced hearing loss continues to be a major occupational health hazard. Despite indications that complex noise environments with significant impulsive components are more hazardous to hearing than steady-state noise, simple energy-averaging techniques are still used to measure the effects on hearing. Meanwhile, animal research and, more recently, large-scale studies of workers' hearing have confirmed that noise kurtosis is critical to the estimation of noise-induced auditory effects. It is now clear that hearing loss increases as kurtosis increases, and the resulting losses appear to be independent of the detailed temporal structure of the noise for fixed values of kurtosis and energy. These findings have important implications for the protection of noise-exposed populations. A better understanding of the role of the kurtosis metric should lead to a new and more accurate method of noise-exposure measurement and hearing risk assessment.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health or the Centers for Disease Control and Prevention.

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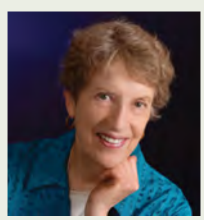

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