

## Review

# Measurement of Non-Steady Noise and Assessment of Occupational Hearing Loss Based on The Temporal Structure of Noise

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Noise-induced hearing loss (NIHL) has become a global public health problem, and the economic burden of hearing loss caused by noise exposure accounts for 19.6% of the economic burden of all risk factors in the workplace (1). The prevalence of occupational NIHL was estimated to be 10% in relevant occupational population in developed countries and 17%–39% (e.g., textile and petrochemical industries), and 53%–67% (e.g., cement and automobile industries) in developing countries in Asia, respectively. (2). In China, occupational noise-induced deafness has become the second primary occupational disease after pneumoconiosis, with the number of reported cases increasing at an average annual rate of 18.68% from 2010 to 2019 (3–4). The prevalence of occupational NIHL in the Chinese occupational population was 21.3%, of which 30.2% was related to high-frequency NIHL (an early sign of NIHL) (2).

Controlling the risk of hearing loss is critical for protecting workers' hearing health and noise exposure measurement and assessment are crucial links within these efforts. At present, workers are often widely exposed to non-steady noise in occupational environments (5). The important difference between steady-state and non-steady noise is the energy distribution (temporal structure), i.e., the former is statistically normal, and the latter is non-normal and time-varying. Animal and human data show that the temporal structure of noise is a risk factor for NIHL (6). Presently, applying noise's temporal structure to quantitative measurement and evaluation of industrial noise has made some progress, but there are few reports on the relevant review. The aim of present paper is thus to review the research progress of measuring and assessing workplace non-steady noise based on the temporal structure of noise.

## Identification of Non-Steady Noise Based on Temporal Structure

This study's definition of non-steady noise is defined

as transient high-energy impulsive noise superimposed on Gaussian background noise (5,7), which differs from the traditional definition (based on noise energy). In the traditional definition, non-steady noise is noise with a fluctuation greater than 3dB(A) determined by the sound level meter with a “slow” dynamic characteristic during the measuring time (8–9), which fails to reflect the temporal structure of non-steady noise.

Measuring the following parameters for the temporal structure of single impulse noise is usually standard when evaluating noise: peak pressure, interpeak interval, and pulse duration (10). Kurtosis, sensitive to and primarily determined by these three above variables, can quantify the impulsiveness of complex noise and is much more practical as a specific metric for the temporal structure of complex noise (6,11–12). It can quantify the noise signal's complexity (6,13).

Kurtosis is a statistical measure of extreme values or outliers relative to a normal distribution (11). The calculation formula is following:

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

where  $\beta$  is the kurtosis,  $x_i$  is the  $i^{\text{th}}$  value of noise amplitude, and  $\bar{x}$  is the sample mean. Kurtosis describes the tendency for a sound to have high amplitude events that depart substantially from underlying, continuous, steady-state noise. It should be noted that kurtosis has high sampling variability since the length of intervals over which kurtosis is determined can affect the outcome (14–15). In practice, the kurtosis of the recorded noise signal is usually computed over consecutive 60-second time windows (without overlap) over the whole measurement duration using a sampling rate of 48 kHz for noise recordings (16).

Figure 1A shows a sample of a steady-state noise, i.e., a flat waveform with a kurtosis value of 3.

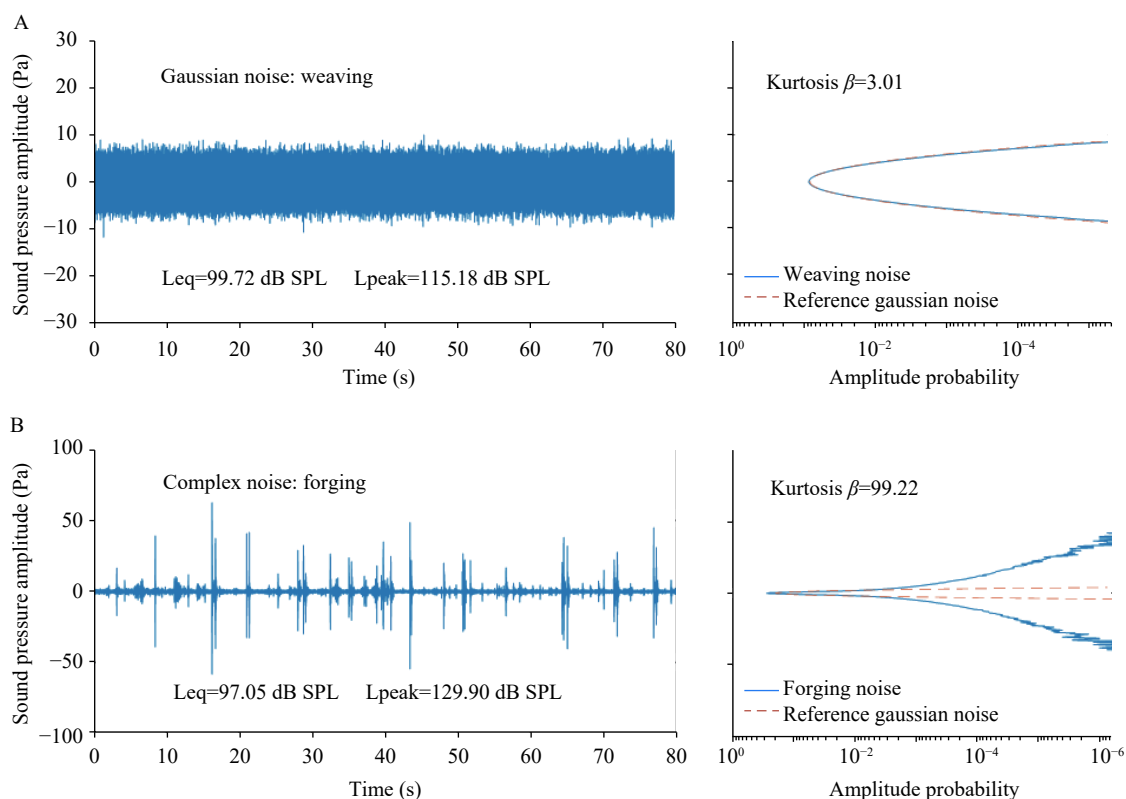


FIGURE 1. Waveforms (left) and amplitude probabilities (right) from two industrial noises: (A) steady-state noise; (B) non-steady (complex) noise. Red lines, background Gaussian noise probabilities. Abbreviation: Leq=equivalent sound pressure level; Lpeak=peak sound pressure level; SPL=sound pressure level.

Figure 1B illustrates an example of a non-steady noise, i.e., a Gaussian background noise punctuated by a temporally complex series of randomly occurring, high-level, impulsive/impact noise transients. The noise waveform and kurtosis of different work types are unique, providing a practical approach for identifying different types of industrial noise (6).

### A Need for Modification to Existing Noise Standards Based on Kurtosis

The international noise exposure standards [e.g., ISO 1999: 2013, ISO 9612 (2009), HSE 2005 and NIOSH 1998] and China's noise exposure measurement standard (GBZ/T 189.8) are based on the "equal energy hypothesis (EEH)" (9,17–20). The energy of the noise (e.g., equivalent continuous A-weighted sound pressure level,  $L_{Aeq}$ ) is considered the only measurement and evaluation criterion.  $L_{Aeq}$  is normalized to a nominal 8-hour working day ( $L_{EX,8h}$ ) or a nominal week of five 8 h working days ( $L_{EX,40h}$ ). However, due to the "peak clipping effect" (i.e., a clip of instrument electronics against high input levels greater than 130 dB and a lacking of a fast enough

time constant to capture impulses) for noise with impulsive components, the  $L_{Aeq}$  measurement technique using noise dosimeter or sound level meter can not reflect the temporal structure of noise and can not capture the peak change (21).

In the existing standards,  $L_{Aeq}$  serves as the sole metric when evaluating NIHL based on the EEH. The EEH assumes that hearing loss caused by noise exposure is proportional to the exposure duration multiplied by the energy intensity, thus implying that hearing loss is independent of the acoustic energy temporal distribution. The problem with the existing standards is that the temporal characteristic of non-Gaussian noise is not taken into account when assessing the effects of noise on hearing. As a result, non-steady noise measurement (especially for noise with a high kurtosis value) is inaccurate, and hearing loss is underestimated when applying the existing standards. Epidemiological data showed that the current ISO 1999 prediction model underestimated the complex noise-induced permanent threshold shift (NIPTS) by over 10 dB HL on average (6,14–15,22); The 85 dB(A) noise exposure limit may still be unsafe due to noises with high kurtosis values (6). Therefore,

it is necessary to apply kurtosis to adjust the energy level in order to more effectively assess NIHL.

### The Role of Kurtosis in Evaluating NIHL

Previous animal studies have found that kurtosis can distinguish the degree of hearing loss caused by different temporal structural noises under the same noise exposure level (13,23). These findings have been confirmed by subsequent epidemiological survey data (24–25). Human evidence demonstrates that the temporal structure of noise is a risk factor for occupational NIHL, in addition to noise level, exposure duration, age, and sex (6,26–27). Complex noise induces more serious hearing damage among workers than steady-state noise [odds ratio (OR)=2.20, 95% confidence interval (CI): 1.78–2.72] (26). Kurtosis had a significant dose-effect relationship with the prevalence of high-frequency NIHL (6,28). NIPTS<sub>346</sub> increased with kurtosis across different cumulative noise exposure (CNE) levels. The notch degree of hearing loss at the high frequencies 3, 4, and 6 kHz deepened with the increase of kurtosis and reached its maximum at 4 kHz (6,28). The underestimation of NIPTS by the ISO 1999 prediction model increases with the increase of kurtosis level (28). Thus, the permissible exposure limit of 85 dB(A) may not be safe, as non-steady noise with a high kurtosis value can aggravate or accelerate early NIHL (6). These data reveal that the kurtosis metric is an adjunct to noise energy for qualifying and assessing non-steady noise in the workplace.

### Methodologies of Applying Kurtosis to Adjust Noise Energy

Currently, there are two adjustment protocols, one is to adjust the noise exposure level (e.g.,  $L_{EX,8h}$  or  $L_{EX,40h}$ ) (6,28), and another is to adjust the exposure duration in CNE (6,28–31). However, due to the ambiguity of the relationship between CNE and NIPTS, and the uncertainty of exposure duration for workers whose jobs change frequently, it is not recommended to adjust the exposure duration in CNE in practice. Instead, an adjustment protocol for noise intensity is preferable (28).

The adjustment protocol applies kurtosis to adjust the noise intensity based on Goley's protocol from animal data (32). The formula is as follows:

$$L_{EX,8h-K} = L_{EX,8h} + \lambda \times \lg(\beta_N/3) \quad (2)$$

In the formula,  $\beta_N$  is the kurtosis value of the noise measured;  $L_{EX,8h-K}$  is kurtosis-adjusted  $L_{EX,8h}$ ; and

$\lambda$  is the adjustment coefficient obtained from the dose-effect relationship between noise exposure and hearing loss. The  $\lambda$  value is recommended as 6.5 based on human data (6,28). The  $L_{EX,8h-K}$  can be calculated as follows:

$$L_{EX,8h-K} = L_{EX,8h} + 6.5 \times \lg(\beta_N/3) \quad (3)$$

where  $\beta_N$  is the average kurtosis value of noise during measurement duration. For example, when  $\beta_N$  is 30, the  $L_{EX,8h}$  or  $L_{EX,40h}$  increases by 6.5 dB(A). After the adjustment of  $L_{EX,8h}$  by kurtosis, this study found that the underestimation of NIPTS<sub>346</sub> by ISO 1999 improved significantly (less than 1.23 dB HL) (6).

Currently, ISO 1999:2013 “Acoustics-Estimation of Noise-Induced Hearing Loss” is being revised based on the adjusting protocol. The National Institute of Occupational Health and Poisoning Control: Chinese Center for Disease Control and Prevention is carrying out the preliminary research project “Kurtosis Based Occupational Noise Exposure Limit and Measurement Standard Revision” on occupational health standards.

### Developing a Measurement Guideline Based on Kurtosis Adjustment

A dedicated personal sound exposure meter (or noise dosimeter) should be developed to have at least one of the following functions: 1) sound recording for further analysis of kurtosis or  $L_{Aeq}$ ; or 2) automatic calculation of kurtosis,  $L_{EX,8h}$ , or  $L_{EX,8h-K}$  for direct reading. A dosimeter prototype with kurtosis function has been successfully developed in China. The direct reading method of kurtosis and  $L_{EX,8h-K}$  values are preferred if the dosimeter with kurtosis function becomes commercially available (28).

The measurement guideline for non-steady noise can be developed based on modifying existing standards, e.g., the ISO 9612 (2009). Measurement procedures may include the following items: field investigation, preparation of instruments, determination of sampling subjects, dosimeter wearing, noise waveform analysis, or direct reading of the device, data analysis, measurement records, and notes of non-steady noise measurements. The condition of using kurtosis adjustment (Formula 3) in the assessment of NIHL is  $L_{EX,8h}$  between 70 and 95 dB(A). For  $L_{EX,8h}$  higher than 95 dB(A), Formula 3 provides a reasonable interpolation (28).

### Outlook

Non-steady noise is the primary type of noise in the workplace. Existing noise measurement and evaluation

standards are not fully applicable to non-steady noise. As a sensitive temporal structural index for non-steady noise exposure, kurtosis can be used as an adjunct parameter of the noise energy to evaluate occupational hearing loss more effectively. The following measures are thus recommended for further research.

1) Further developing and improving the database on the noise-exposed population through large-scale and well-designed epidemiological investigations. The database should cover noise exposure data with different kurtosis levels and include different noise-hazard industries and their main types of work. In addition, it is also necessary to develop databases on the statistical distribution of hearing threshold levels from the general population in Asian countries.

2) Methodological studies applying kurtosis to adjust noise intensity. More population epidemiological data are needed to verify the applicability and effectiveness of the new parameter of the noise intensity adjusted by kurtosis in assessing occupational hearing loss.

3) Revisions of the measurement and assessment standards for occupational noise. The population data can reconstruct the dose-response (effect) relationship based on the kurtosis adjustment, which is critical for revising existing noise exposure standards. In addition, a dedicated personal sound exposure meter (or noise dosimeter) with a function of waveform analysis or direct reading for kurtosis and  $L_{EX,8\text{ h-K}}$  (or  $L_{EX,40\text{ h-K}}$ ) needs to be further commercialized and available.

4) Studies on the influence of noise's temporal structure on principal characteristics of occupational hearing loss. These affected characteristics may include the notching phenomenon of high-frequency hearing threshold, the maximum hearing threshold shift at different frequencies, and the onset period or latency of hearing loss related to exposure duration. Strengthening study of the principal characteristics of occupational hearing loss related to the temporal structure of noise is critical for the diagnosis and early prevention of NIHL or noise-induced deafness and for improving the hearing protection plan of workers.

**Funding:** This work was supported by the National Key R&D Program of China (2022YFC2503200, 2022YFC2503203); the Pre-research project on occupational health standards (20210102); and the National Institutes of Health, National Institute on Deafness and Other Communication Disorders, United States (1R01DC015990).

doi: 10.46234/ccdcw2023.012

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Submitted: November 20, 2022; Accepted: January 16, 2023

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