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:

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

where β is the kurtosis, x_i is the ith 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.
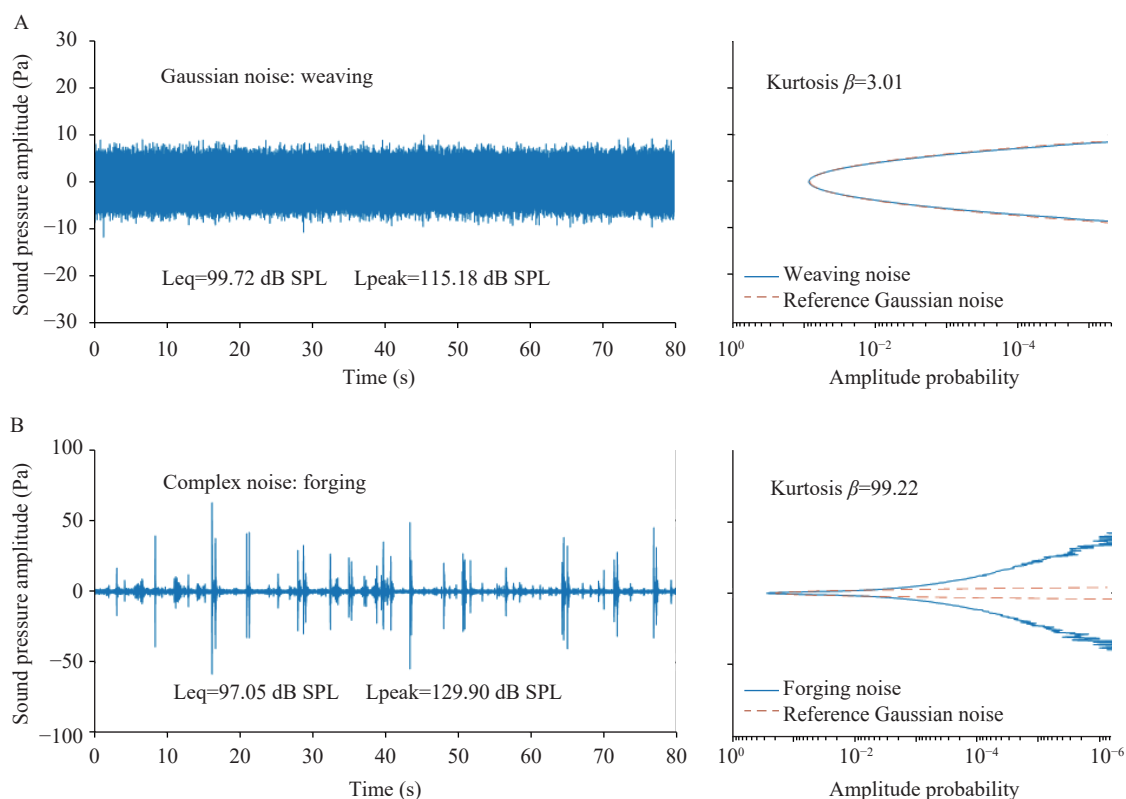
FIGURE 1. Waveforms (left) and amplitude probabilities (right) from two industrial noises: (A) steady-state noise; (B) non-steady (complex) noise. Red lines, background Gaussian noise probabilities.
Abbreviation: Leq=equivalent sound pressure level; Lpeak=peak sound pressure level; SPL=sound pressure 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 ($L_{EX,8\ h}$) or a nominal week of five 8 h working days ($L_{EX,40\ h}$). 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, LAeq 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). $NIPTS_{346}$ 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., $L_{EX,8 h}$ or $L_{EX,40 h}$) (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:

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

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

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

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

where β_N is the average kurtosis value of noise during measurement duration. For example, when β_N is 30, the $L_{EX,8 h}$ or $L_{EX,40 h}$ increases by 6.5 dB(A). After the adjustment of $L_{EX,8 h}$ by kurtosis, this study found that the underestimation of $NIPTS_{346}$ 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, $L_{EX,8 h}$, or $L_{EX,8 h}$-K for direct reading. A dosimeter prototype with kurtosis function has been successfully developed in China. The direct reading method of kurtosis and $L_{EX,8 h}$-K values is 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 $L_{EX,8 h}$ between 70 and 95 dB(A). For $L_{EX,8 h}$ 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 $L_{EX,8\,h}$-K (or $L_{EX,40\,h}$-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.

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REFERENCES

1. GBD 2016 Occupational Risk Factors Collaborators. Global and regional burden of disease and injury in 2016 arising from occupational exposures: a systematic analysis for the Global Burden of Disease Study 2016. Occup Environ Med 2020;77(3):133 – 41. http://dx.doi.org/10.1136/oemed-2019-106008.
2. Zhou JN, Shi ZH, Zhou LF, Hu Y, Zhang MB. Occupational noise-induced hearing loss in China: a systematic review and meta-analysis. BMJ Open 2020;10(9):e039576. http://dx.doi.org/10.1136/bmjopen-2020-039576.
3. Sun X. Occupational noise exposure and worker's health in China. China CDC Wkly 2021;3(18):375 – 77. http://dx.doi.org/10.46234/ccdcw2021.102.
4. Chen YL, Zhang MB, Qiu W, Sun X, Wang X, Dong YW, et al. Prevalence and determinants of noise-induced hearing loss among workers in the automotive industry in China: a pilot study. J Occup Health 2019;61(5):387 – 97. http://dx.doi.org/10.1002/1348-9585.12066.
5. Suter AH. Occupational hearing loss from non-Gaussian noise. Semin Hear 2017;38(3):225 – 62. http://dx.doi.org/10.1055/s-0037-1603726.
6. Zhang MB, Qiu W, Xie HW, Xu XH, Shi ZH, Gao XJ, et al. Applying kurtosis as an indirect metric of noise temporal structure in the assessment of hearing loss associated with occupational complex noise exposure. Ear Hear 2021;42(6):1782 – 96. http://dx.doi.org/10.1097/AUD.0000000000001068.
7. Hamernik RP, Qiu W. Energy-independent factors influencing noise-induced hearing loss in the chinchilla model. J Acoust Soc Am 2001;110(6):3163 – 8. http://dx.doi.org/10.1121/1.1414707.
8. Ministry of Health of the People's Republic of China. GBZ 2.2-2007 Occupational exposure limits for hazardous agents in the workplace, Part 2: Physical agents. Beijing: People's Medical Publishing House, 2007. (In Chinese).
9. Ministry of Health of the People's Republic of China. GBZ/T 189.8-2007 Measurement of physical agents in workplace, Part 8: Noise. Beijing: Standards Press of China, 2007. (In Chinese).
10. Henderson D, Hamernik RP. Impulse noise: critical review. J Acoust Soc Am 1986;80(2):569 – 84. http://dx.doi.org/10.1121/1.394052.
11. Qiu W, Zhang MB, Hu WJ, Sun X. Application of the kurtosis metric to the assessment of hearing loss associated with occupational noise exposure. China CDC Wkly 2021;3(18):390 – 93. http://dx.doi.org/10.46234/ccdcw2021.105.
12. Qiu W, Hamernik RP, Davis RI. The value of a kurtosis metric in estimating the hazard to hearing of complex industrial noise exposures. J Acoust Soc Am 2013;133(5):2856 – 66. http://dx.doi.org/10.1121/1.4799813.
13. Müller RAJ, Von Benda-Beckmann AM, Halvorsen MB, Ainslie MA. Application of kurtosis to underwater sound. J Acoust Soc Am 2020;148(2):780. http://dx.doi.org/10.1121/10.0001631.
14. Zhang MB, Hu Y, Qiu W, Gao XJ, Zeng AK, Shi ZH, et al. Developing a guideline for measuring workplace non-Gaussian noise exposure based on kurtosis adjustment of noise level in China. Front Public Health 2022;10:1003203. http://dx.doi.org/10.3389/fpubh.2022.1003203.
15. Zhang MB, Gao XJ, Murphy WJ, Kardous CA, Sun X, Hu WJ, et al.

Estimation of occupational noise-induced hearing loss using kurtosis-adjusted noise exposure levels. Ear Hear 2022;43(6):1881 – 92. http://dx.doi.org/10.1097/AUD.0000000000001223.

16. Tian Y, Ding WX, Zhang MB, Zhou TS, Li JS, Qiu W. Analysis of correlation between window duration for kurtosis computation and accuracy of noise-induced hearing loss prediction. J Acoust Soc Am 2021;149(4):2367 – 76. http://dx.doi.org/10.1121/10.0003954.

17. ISO (International Standard Organization). ISO 1999:2013. Acoustics-estimation of noise-induced hearing loss. Geneva, Switzerland: International Organization for Standardization, 2013. https://www.iso.org/standard/45103.html.

18. International Standard Organization (ISO). ISO 1999:1990. Acoustics-determination of occupational noise exposure and estimation of noise-induced hearing impairment. Geneva, Switzerland: International Organization for Standardization, 2013. https://www.iso.org/standard/6759.html.

19. HSE (Health and Safety Executive). The control of noise at work regulations 2005: guidance on regulations. UK: HSE; 2005. HMSO PublicationNo1643. https://www.legislation.gov.uk/uksi/2005/1643/contents/made.

20. National Institute for Occupational Safety and Health (NIOSH). Criteria for a recommended standard: occupational noise exposure. Cincinnati: NIOSH; 1998. DHHS (NIOSH) Publication No. 98-126. https://www.cdc.gov/niosh/docs/98-126/pdfs/98-126.pdf?id=10.26616/NIOSHPUB98126.

21. Davis RR, Clavier O. Impulsive noise: a brief review. Hear Res 2017;349:34 – 6. http://dx.doi.org/10.1016/j.heares.2016.10.020.

22. Lempert B. ISO estimates of noise-induced hearing impairment. J Acoust Soc Am 2019;145(6):3640. http://dx.doi.org/10.1121/1.5111862.

23. Hamernik RP, Qiu W, Davis B. The effects of the amplitude distribution of equal energy exposures on noise-induced hearing loss: the kurtosis metric. J Acoust Soc Am 2003;114(1):386 – 95. http://dx.doi.org/10.1121/1.1582446.

24. Davis RI, Qiu W, Hamernik RP. Role of the kurtosis statistic in evaluating complex noise exposures for the protection of hearing. Ear Hear 2009;30(5):628 – 34. http://dx.doi.org/10.1097/AUD.0b013e318 1b527a8.

25. Zhang MB, Xie HW, Zhou JN, Sun X, Hu WJ, Zou H, et al. New metrics needed in the evaluation of hearing hazard associated with industrial noise exposure. Ear Hear 2021;42(2):290 – 300. http://dx.doi.org/10.1097/AUD.0000000000000942.

26. Shi ZH, Zhou JN, Huang YW, Hu Y, Zhou LF, Shao YQ, et al. Occupational hearing loss associated with non-Gaussian noise: a systematic review and meta-analysis. Ear Hear 2021;42(6):1472 – 84. http://dx.doi.org/10.1097/AUD.0000000000001060.

27. Zhou LF, Ruan XY, Wang TS, Xie HW, Hu Y, Shi ZH, et al. Epidemiological characteristics of hearing loss associated with noise temporal structure among manufacturing workers. Front Integr Neurosci 2022;16:978213. http://dx.doi.org/10.3389/fnint.2022.978213.

28. Zhang MB, Gao XJ, Qiu W, Sun X, Hu WJ. The role of the kurtosis metric in evaluating the risk of occupational hearing loss associated with complex noise — Zhejiang Province, China, 2010-2019. China CDC Wkly 2021;3(18):378 – 82. http://dx.doi.org/10.46234/ccdcw2021.103.

29. Shi ZH, Wang X, Gao XJ, Xie HW, Zhou LF, Zhang MB. Assessment of occupational hearing loss associated with non-Gaussian noise using the kurtosis-adjusted cumulative noise exposure metric: a cross-sectional survey. Front Psychol 2022;13:870312. http://dx.doi.org/10.3389/fpsyg.2022.870312.

30. Xie HW, Qiu W, Heyer NJ, Zhang MB, Zhang P, Zhao YM, et al. The use of the kurtosis-adjusted cumulative noise exposure metric in evaluating the hearing loss risk for complex noise. Ear Hear 2016;37(3):312 – 23. http://dx.doi.org/10.1097/AUD.0000000000000251.

31. Zhao YM, Qiu W, Zeng L, Chen SS, Cheng XR, Davis RI, et al. Application of the kurtosis statistic to the evaluation of the risk of hearing loss in workers exposed to high-level complex noise. Ear Hear 2010;31(4):527 – 32. http://dx.doi.org/10.1097/AUD.0b013e3181d94e68.

32. Goley GS, Song WJ, Kim JH. Kurtosis corrected sound pressure level as a noise metric for risk assessment of occupational noises. J Acoust Soc Am 2011;129(3):1475 – 81. http://dx.doi.org/10.1121/1.3533691.