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Applying Kurtosis as an Indirect Metric of Noise Temporal Structure in the Assessment of Hearing Loss Associated With Occupational Complex Noise Exposure

Meibian Zhang,[1] Wei Qiu,[2] Hongwei Xie,[1] Xiaohui Xu,[3] Zhihao Shi,[4] Xiangjing Gao,[1] Lifang Zhou,[1] Hua Zou,[1] Weijiang Hu,[5] and Xin Sun[5]

Objective: The association of occupational noise-induced hearing loss (NIHL) with noise energy was well documented, but the relationship between occupational noise and noise temporal structure is rarely reported. The objective of this study was to investigate the principal characteristics of the relationship between occupational NIHL and the temporal structure of noise.

Methods: Audiometric and shift-long noise exposure data were collected from 3102 Chinese manufacturing workers from six typical industries through a cross-sectional survey. In data analysis, A-weighted 8-h equivalent SPL ($L_{Aeq.8h}$), peak SPL, and cumulative noise exposure (CNE) were used as noise energy indicators, while kurtosis (β) was used as the indicator of noise temporal structure. Two NIHL were defined: (1) high-frequency noise-induced hearing loss (HFNIHL) and (2) noise-induced permanent threshold shift at test frequencies of 3, 4, and 6 kHz (noise-induced permanent threshold shift [$NIPTS_{346}$]). The noise characteristics of different types of work and the relationship between these characteristics and the prevalence of NIHL were analyzed.

Results: The noise waveform shape, with a specific noise kurtosis, was unique to each type of work. Approximately 27.92% of manufacturing workers suffered from HFNIHL, with a mean $NIPTS_{346}$ of 24.16 ± 14.13 dB HL. The Spearman correlation analysis showed that the kurtosis value was significantly correlated with the difference of peak SPL minus its $L_{Aeq.8h}$ across different types of work ($p < 0.01$). For a kurtosis-adjusted CNE, the linear regression equation between HFNIHL% and CNE for complex noise almost overlapped with Gaussian noise. Binary logistic regression analysis showed that $L_{Aeq.8h}$, kurtosis, and exposure duration were the key factors influencing HFNIHL% ($p < 0.01$). The notching extent in NIPTS at 4 kHz became deeper with the increase in $L_{Aeq.8h}$ and kurtosis. HFNIHL% increased most rapidly during the first 10 years of exposure. HFNIHL% with β ≥ 10 was significantly higher than that with β < 10 ($p < 0.05$), and it increased with increasing kurtosis across different CNE or $L_{Aeq.8h}$ levels. When $L_{Aeq.8h}$ was 80 to 85 dB(A), the HFNIHL% at β ≥ 100 was significantly higher than that at 10 ≤ β < 100 or β < 10 ($p < 0.05$ and $p < 0.01$, respectively).

Conclusions: In the evaluation of hearing loss caused by complex noise, not only noise energy but also the temporal structure of noise must be considered. Kurtosis of noise is an indirect metric that is sensitive to the presence of impulsive components in complex noise exposure, and thus, it could be useful for quantifying the risk for NIHL. It is necessary to re-evaluate the safety of permissible exposure limit of 85 dB(A) as noise with a high kurtosis value can aggravate or accelerate early NIHL.

Key words: Complex noise, Hearing loss, Kurtosis, Occupational exposure, Prevalence.

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[1]Occupational Health and Radiation Protection Institute, Zhejiang Provincial Center for Disease Control and Prevention, Hangzhou, Zhejiang, China; [2]Auditory Research Laboratory, State University of New York at Plattsburgh, New York, USA; [3]Department of Epidemiology and Biostatistics, School of Public Health, Texas A&M Health Science Center, Texas, USA; [4]School of Medicine, Ningbo University, Ningbo, Zhejiang, China; and [5]National Institute of Occupational Health and Poisoning Control, China Center for Disease Control and Prevention, Beijing, China

INTRODUCTION

Noise-induced hearing loss (NIHL), a type of progressive sensorineural hearing loss, is a global public health problem (Basner et al. 2014; Le et al. 2017). It is estimated that 10% of the global population is exposed to noise pollution, and of those, 5.3% suffer from NIHL (Oishi & Schacht 2011). Moreover, 16% of adult hearing loss cases might be associated with occupational exposure to noise (Beyan et al. 2016). Occupational NIHL is one of the most prevalent occupational diseases worldwide. Approximately 600 million workers are estimated to be exposed to harmful levels of noise globally (Soltanzadeh et al. 2014), and more than 10% of the workers in developed countries suffer from NIHL (Konings et al. 2009). In China, occupational NIHL is currently the second most common occupational disease, with an annual increase of 20% (National Health Commission of China 2019). It was estimated that at least 10 million workers in China are exposed to harmful noise levels at work (Chen et al. 2017). The prevalence of NIHL in the occupational population was estimated to exceed 20% (Li et al. 2014). In some developing countries, it is reported that the prevalence of occupational NIHL ranges from 18% to 67% (Nandi & Dhatrak 2008; Fuente & Hickson 2011).

In terms of its temporal structure, industrial noise can be divided into steady-state, continuous (Gaussian) noise, and non-Gaussian complex noise. Complex noise is composed of transient high-energy impulsive noise superimposed on Gaussian background noise (Hamernik & Qiu 2001). Animal experiments (Hamernik et al. 2003, 2007; Qiu et al. 2006, 2013) showed that for the same noise level and noise spectra, non-Gaussian complex noise produces more NIHL than Gaussian noise, and the temporal distribution of energy is an important factor in the evaluation of hearing loss caused by complex noise. Occupational epidemiologic studies (Davis et al. 2009; Zhao et al. 2010; Xie et al. 2016; Zhang et al. 2020) reinforced these results.

Complex noise is common in industrial settings. Because the complex noise contains impulsive components, it is challenging to measure the complex noise in industrial settings. Conventional noise measurement techniques are not suitable for complex noise measurement due to the peak clipping effect of impulse noise (Davis & Clavier 2017). Moreover, these conventional

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noise measurement methods (using dosimeters or sound level meters) cannot reflect the temporal structure of the noise. For a single-impulse noise, the following parameters are usually recommended to be measured: peak level, rise and decay time, and impulse duration (Henderson & Hamernik 1986; Starck et al. 2003). This measurement is challenging for industrial noise measurements because impulses in a work shift may have different peak intensities, inter-transient intervals, and durations, all of which are known to affect the outcome of noise exposure. Qiu et al. (2013) demonstrated that kurtosis is sensitive to and largely determined by these three earlier variables. Therefore, kurtosis of the noise can provide an "indirect" metric sensitive to the presence of impulse noise in complex noise exposure.

Kurtosis (β) is a statistical measure that defines how heavily the tails of distribution differ from the tails of a Gaussian distribution. It is defined as the ratio of the fourth-order central moment to the squared second-order central moment of a distribution. Kurtosis can be used to distinguish complex noise from Gaussian noise in the workplace (Goley et al. 2011; Qiu et al. 2016). In most workplaces, workers are exposed to complex noise as it comes from many noise sources. Noise can be air- or structure-borne, and the acoustic signals might change or be augmented by reflections from the floor, walls, ceiling, and machinery surfaces (Suter, 2017). Workers, particularly those in manufacturing industries, are increasingly at risk of hearing loss caused by complex noise exposure. Hearing loss is considered to be associated with noise temporal structure in addition to noise energy (Qiu et al. 2013; Zhang et al. 2020). The effect of the noise temporal structure on NIHL greatly challenges the appropriateness of the international noise exposure standards (e.g., ISO 1999, 2013) for complex noise, in which the noise energy (e.g., the equivalent SPL, L_{eq}) serves as the sole metric when evaluating NIHL based on the equal energy hypothesis (EEH) (MOH, Ministry of Health 2007; National Health Commission of China 2007; NIOSH 2018;). 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 approach in ISO 1999 is generally considered to be appropriate for assessing hearing loss due to Gaussian or steady-state noise, but not for assessing hearing loss due to complex noise (Davis & Clavier 2017; Suter 2017; Zhou et al. 2020).

Considering the potential role of noise temporal structure in NIHL, it is necessary to examine noise exposure characteristics and NIHL in populations with different occupations. The noise temporal structure might help occupational and environmental medicine (OEM) physicians and other occupational health professionals understand workers' real noise exposure history by determining the different workplace noise types. In addition to noise energy, noise structure should also be considered in the characterization of workers' noise exposure. Due to occupational exposure to complex noise, key features of NIHL need to be re-examined, including key influencing factors, the notch at the high-frequency hearing threshold, the development pattern of hearing loss related to exposure duration, and the permissible exposure limit of 85 dBA (ACOEM 2018). Although the relationship between NIHL and noise energy is well understood, the relationship between NIHL and noise structure is rarely reported. In this study, a cross-sectional survey was conducted to investigate the correlation between occupational NIHL and the temporal structure of noise among Chinese manufacturing workers.

MATERIALS AND METHODS

Subjects

A cross-sectional survey was designed for this study. A total of 3102 manufacturing workers exposed to high levels of noise were recruited in Zhejiang, China from 2015 to 2018. These workers worked in six typical manufacturing industries, namely, textile, paper making, furniture, automobile, metal product, and general equipment manufacturing. The noise of the textile and paper industry is mainly steady-state noise. In the other four industries, complex noise is the main noise type.

Participant inclusion criteria were as follows: (1) continuously working within the same job category and work site for their entire employment period; (2) no history of exposure to ototoxic medications used for lifesaving conditions, head wounds, or ear diseases; (3) no history of military service or shooting activities; (4) no or minimal use of hearing protection (determined from the noise exposure questionnaire and interview); (5) no history of diabetes; and (6) no co-exposure to noise and ototoxic organic solvents and heavy metals. In this study, the following measures were taken to avoid the selection of work positions exposed to organic solvents and/or heavy metals: (i) Adopt the expert consultation method to conduct preliminary screening for the industries exposed only to noise and not to organic solvents and heavy metals; (ii) In selected industries, field surveys are conducted by industrial hygienists to select noise-only work types (no exposure to organic solvents and heavy metals) by identifying occupational risk factors in the workplace. At the same time, through the face-to-face questionnaire survey, the field survey results were verified; (iii) If in doubt, air samples from each workplace will be collected and sent to a laboratory for analysis to detect the presence of organic solvents and heavy metals. The test method is based on the Chinese Occupational Health Standard – "Determination of toxic substances in the air of the workplace" (GBZ/T 300, 2017). The participants were asked to sign informed consent forms, which ensured that they understood the study's purpose, procedures, and contents. The study protocol was approved by the ethics committee of the Zhejiang Center for Disease Control and Prevention, China (Zhejiang CDC, approval reference number: ZJCDC-T-043-R).

Questionnaire Survey and Field Investigation

A face-to-face questionnaire survey was administered. Individual information, which included general personal information (e.g., age, sex, smoking, and alcohol use) and information on occupational history (e.g., factory, workshop, type of work, noise exposure duration, and HPD use) and general health conditions (e.g., history of ear disease, use of ototoxic drugs, blood pressure, diabetes, and genetic diseases), was collected for each participant. Besides, a field investigation of the workplaces was conducted to understand the distribution of noise sources, enterprise products, production processes, number of workers exposed to the noise, and measures taken to reduce the noise level.

Noise Measurement and Analyses

A digital noise recorder (ASV5910-R, Hangzhou Aihua Instruments Co., Ltd., China) was used to record a shift-long personal noise exposure for each participant. The instrument uses a ¼-inch pre-polarized condenser microphone with a broad response frequency (20 Hz to 20 kHz) and high sensitivity level

(2.24 mV/Pa). The measurement ranges from 40 dB(A) to 141 dB(A). The recorder can work continuously for 23 hr under full charge. The noise was recorded continuously with a 32-bit resolution and at a sampling rate of 48 kHz. The full-shift noise exposure of each participant was recorded. It was performed one time for each participant. Before recording, a hygienist confirmed with each participant that this was the noise they were typically exposed to on an average working day. The members of the research team monitored the noise collection of individual participants in the workplace. The recording was saved on a 32-GB microSD card and then transferred to a computer for subsequent analysis. The microphone was placed on the shoulder of each participant at the start of the work shift and collected at the end of the shift. The participants were trained to wear the recorder properly.

A program using the MATLAB software was developed to analyze the shift-long noise and obtain the A-weighted SPL (i.e., 8-h continuous equivalent, $L_{Aeq.8h}$), peak SPL, and kurtosis (β). As a measurement index of the temporal structure of complex noise, kurtosis represents the impulsiveness of noise exposure (Goley et al. 2011; Qiu et al. 2016). The greater the kurtosis, the higher the complex noise impulsiveness. This statistic simplifies the time-domain variables that affect hearing, such as the peak value, peak duration, and inter-peak distribution. It combines these into an easy-to-calculate parameter that simplifies the classification of complex noise (Xie et al. 2016). A kurtosis value was computed in each consecutive 40-s time window of the shift-long noise recording. In this study, a mean $\beta = 10$ was used as a boundary to distinguish complex noise from steady-state noise (Davis et al. 2009). Noise with a mean $\beta \geq 10$ was defined as complex noise, and that with a mean $\beta < 10$ was defined as steady-state noise. Cumulative noise exposure (CNE) was used to quantify the total noise exposure (Earshen 1986). The CNE was calculated by combining $L_{Aeq.8h}$ and the exposure duration (T) as follows:

$$\mathrm{CNE} = \mathrm{L}_{\mathrm{Aeq,8h}} + 10\log T$$

Audiometric Test and Analysis

Each participant underwent a general physical examination and an audiometric test. The pure tone air conduction HTLs at 0.5, 1.0, 2.0, 3.0, 4.0, 6.0, and 8.0 kHz were measured in each ear. The audiometric test was performed in an audiometric booth on a mobile medical examination vehicle using an audiometer (Madsen OB40, Denmark) with an air conduction headphone (Sennheiser HDA 300). Before the test, the audiometer and headphone were calibrated for hearing thresholds by the Zhejiang Institute of Metrology of China, according to the Chinese standard (i.e., Acoustics—Audiometric test methods—Part 1: Pure-tone air and bone conduction audiometry, GB/T 16296.1-2018, originated from the ISO 8253-1:2010). The audiogram for each participant was determined at least 16 h after the last occupational noise exposure. Measured HTLs at each frequency in each worker were adjusted by subtracting the age- and sex-specific HTL according to Table B.3 of ISO 1999 (2013). High-frequency noise-induced hearing loss (HFNIHL) was defined as adjusted HTL ≥ 30 dB, in either ear, at one or more of the HTLs at 3.0, 4.0, and 6.0 kHz (Zhao et al. 2010; Xie et al. 2016; Chen et al. 2019). The noise-induced permanent threshold shift (NIPTS) at frequencies of 3, 4, and 6 kHz ($NIPTS_{346}$) was calculated using the formulas in ISO 1999 (2013).

Statistical Analyses

A one-way analysis of variance was used to compare $NIPTS_{346}$, $L_{Aeq.8h}$, and kurtosis among the different work types. Univariate linear regression analysis was used to obtain the linear regression equation between HFNIHL% and each risk factor (e.g., CNE, kurtosis, $L_{Aeq.8h}$, and exposure duration). Binary logistic regression analysis was used to analyze the odds ratio (OR) and 95% confidence interval values of key factors affecting HFNIHL% (as a categorical dependent variable). Multiple linear regression analysis was used to analyze the influence of key factors on mean $NIPTS_{346}$ (as a continuous dependent variable). The Chi-square test was used to compare HFNIHL% across different $L_{Aeq.8h}$, kurtosis, and CNE groups. The Spearman correlation analysis was used to analyze the correlation of the kurtosis value with the difference of peak SPL (L_{peak}) minus its $L_{Aeq.8h}$ across different types of work. Continuous variables are presented as mean ± SD, and categorical variables are presented as percentages. Differences with a $p < 0.05$ were considered statistically significant.

RESULTS

Principal Characteristics of Noise Exposure Among Manufacturing Workers

Noise Exposure Associated With Intensity and Kurtosis Among Manufacturing Workers • Table 1 lists the general characteristics of the participants. The mean age of these workers was 35.72 ± 9.34 years, and the mean exposure duration was 9.15 ± 7.68 years. The percentage of male workers was 71.92%. The average $L_{Aeq.8h}$ among the manufacturing workers from all six industries was 89.43 ± 6.81 dB(A), which exceeds the occupational exposure limit (OEL) of 85 dB(A). In detail, 77.6%, 45.33%, 19.66%, and 5.61% of manufacturing workers were exposed to harmful noise levels greater than 85, 90, 95, and 100 dB(A), respectively. The proportion of workers exposed to high levels of noise varied from industry to industry: 86.14% of workers from the paper-making industry were occupationally exposed to noise levels above 85 dB(A). This was followed by the textile (85.52%), metal products (81.30%), automobile (80.16%), furniture (77.08), and general equipment (65.41%) industries. As shown in Table 1, the furniture industry has the highest mean kurtosis value, with 54.40% of workers whose kurtosis exceeds 100. The metal products, general equipment, and automotive industries are next, with an average kurtosis between 10 and 50. The lowest kurtosis was found in the textile or paper industry, near or below 10.

Identification of Noise Type Based on Work Type, Waveform, and Kurtosis • Figure 1 illustrates the waveforms, amplitude probabilities, and peak SPL distributions from 13 typical industrial noises. The higher the kurtosis value, the heavier the tail of the probability distribution. Figure 1A show that the waveforms of weaving and spinning activities in the textile industry and that of pulping activity in the paper-making industry are flat with a kurtosis value of 3, and SPLs remain relatively stable. Figure 1B–E illustrates that the waveforms of complex noise generated from other noise activities (e.g., nail gunning, woodworking, cold heading, metal processing, welding, stamping, polishing, punching, and forging), are presented as randomly instantaneous impulses with a kurtosis β > 10, embedded on the background Gaussian noise. Different types of work can be roughly distinguished according to different noise kurtosis values.

TABLE 1. Prevalence of noise-induced hearing loss among manufacturing workers in different industries

		General information on workers				$L_{Aeq.8h}$ [dB(A)]		Kurtosis					
Noise type	Industry	n	Age (y)	Male [n (%)]	Exposure duration (y)	Mean	≥85 (%)	Mean	≥10 (%)	≥50 (%)	≥100 (%)	HFNIHL (%)	$NIPTS_{346}$ (dB)
Gaussian	Textile	460	33.10 ± 8.52	235 (51.09)	8.72 ± 6.69	94.99 ± 8.30	86.50	9.94 ± 12.59	28.98	1.11	0.50	33.04	25.25 ± 14.46
	Paper	101	47.70 ± 9.84	66 (65.35)	11.7 ± 8.61	88.70 ± 4.49	86.10	11.03 ± 10.11	39.80	2.04	0	27.72	23.79 ± 13.10
	Average	561	35.75 ± 10.43	301(53.65)	9.26 ± 7.16	93.86 ± 8.12	86.50	10.13 ± 12.18	32.30	1.30	0.40	32.09	24.99 ± 14.40
Complex	Furniture	432	34.91 ± 10.21	377 (87.27)	5.37 ± 5.55	87.97 ± 5.17	77.10	164.71 ± 153.74	100	76.85	54.40	35.18	27.11 ± 14.35
	Automobile	1023	35.12 ± 8.10	833 (81.43)	10.31 ± 8.40	88.77 ± 5.00	80.20	25.64 ± 36.98	80.61	9.96	2.84	24.83	23.07 ± 13.90
	Metal product	369	37.32 ± 9.64	260 (70.46)	7.81 ± 7.35	90.82 ± 6.58	81.30	34.67 ± 44.03	82.98	19.40	8.36	25.47	23.79 ±14.38
	General equipment	717	36.21 ± 9.30	460 (64.16)	10.39± 7.45	87.07 ± 7.16	65.40	34.24 ± 44.03	94.55	18.11	3.39	25.94	23.78 ± 13.74
	Average	2541	35.71 ± 9.09	1930 (76.0)	9.13 ± 7.79	88.45 ± 6.60	75.60	53.02± 89.06	88.50	25.90	13.20	27.00	23.98 ± 14.06
Total	—	3102	35.72 ± 9.34	2231 (71.92)	9.15 ± 7.68	89.43 ± 6.81	77.60	45.26 ± 82.44	77.62	21.24	10.79	27.92	24.16 ± 14.13

HFNIHL, high-frequency noise-induced hearing loss; $NIPTS_{346}$, noise-induced permanent threshold shift at 3, 4, and 6 kHz frequencies.

Table 2 shows the noise levels and kurtosis values of 13 typical work types in six industries. Different industries have different kurtosis values and $L_{Aeq.8h}$ levels. For example, weaving, spinning, and electroplating processes produced relatively high levels of $L_{Aeq.8h}$; nail gunning, woodworking, and electroplating processes generated relatively high kurtosis values of noise exposure. There was no correlation between noise level and kurtosis among the different work types ($p > 0.05$). Thus, each noise activity had a specific value of noise kurtosis and noise level.

Principal Characteristics of NIHL Associated With Noise Energy and Kurtosis

Prevalence of NIHL Among Manufacturing Workers • Table 1 shows that the average HFNIHL% in the six industries was 27.92%, with a mean $NIPTS_{346}$ of 24.16 ± 14.13 dB HL. Significant differences were observed in HFNIHL% among the six industries ($p < 0.01$). Furniture manufacturing workers had the highest HFNIHL% (35.18%), followed by textile, paper, general equipment, metal products, and automobile manufacturing. Table 2 shows significant differences in $NIPTS_{346}$ among the work types ($p < 0.01$). The level of $NIPTS_{346}$ among the manufacturing workers, who were engaged in the 13 work types, ranged between 20 dB HL and 55 dB HL. The Spearman correlation analysis showed that the kurtosis value calculated using an 80-s time window was significantly associated with the difference of peak SPL (L_{peak}) minus its $L_{Aeq.8h}$ across different types of work ($p < 0.01$).

Key Factors Influencing the Prevalence of NIHL • Table 3 shows the binary logistic regression analysis results of the key factors affecting HFNIHL%. The order of the ORs was as follows: $OR_{LAeq.8h} > OR_{kurtosis} > OR_{sex} > OR_{age} > OR_{duration}$. All ORs were between 1 and 2. The multiple linear regression analysis showed $L_{Aeq.8h}$, kurtosis, or exposure duration had a significant effect on mean $NIPTS_{346}$ ($p < 0.01$).

Figure 2 demonstrates that there was a strong linear relationship between HFNIHL% and CNE, kurtosis, $L_{Aeq.8h}$, and exposure duration (ED). Figure 2A shows that the linear regression equation between HFNIHL% and CNE for complex noise is: HFNIHL% = 0.019 CNE – 1.493 ($R^2 = 0.979$), and the equation between HFNIHL% and CNE for Gaussian noise is: HFNIHL% = 0.019 CNE – 1.579 ($R^2 = 0.940$). The average difference of HFNIHL% (complex noise versus Gaussian noise) in the two equations was 7.63%. Figure 2B demonstrates that after CNE was adjusted by kurtosis, the two linear equations were almost overlapped. The average difference of HFNIHL% between complex noise and Gaussian noise was significantly reduced from 7.63% to 1.12%. The linear regression equations for kurtosis, $L_{Aeq.8h}$, and exposure duration in Figure 2C–E are as follows: HFNIHL% = 0.043 β + 0.100 ($R^2 = 0.911$, when CNE < 100), HFNIHL% = 0.101 $L_{Aeq.8h}$ + 0.022 ($R^2 = 0.988$), and HFNIHL% = 0.121 ED −0.053 ($R^2 = 0.990$). When 90 ≤ CNE<95 or 95 ≤ CNE<100, the average HFNIHL% was lower than expected as shown in Figure 2A and B, and when 60 ≤ β < 100, the average HFNIHL% was also lower than expected as shown in Figure 2C.

Symmetrical and Notching Phenomena of NIHL Associated With Kurtosis • Figure 3A shows that the average NIPTS curves for the left and right ears almost overlapped across the test frequencies. Both exhibited a 'V' shape notch at the high frequencies. The average NIPTS increased gradually with frequencies from 0.5 kHz to 4 kHz. Subsequently, it gradually decreased to 8 kHz. The mean NIPTS of the high frequencies 3, 4, and 6 kHz was 19.19 ± 11.85 dB HL, which was significantly higher than that of the low frequencies (0.5, 1, and 2 kHz), which was 15.42 ± 6.69 dB HL. The symmetry of hearing thresholds was not affected by $L_{Aeq.8h}$ or kurtosis levels (data not shown). It can be seen from Figure 3B and C that the notch degree of hearing loss at the high frequencies 3, 4, and 6 kHz deepened with the increase of $L_{Aeq.8h}$ and kurtosis, and reached the maximum at the frequency of 4 kHz.

Patterns of NIHL Development in Association With Exposure Duration, Noise Level, and Kurtosis • Figure 4A shows that when $L_{Aeq.8h}$ was greater than 85 dB(A), HFNIHL% increased more rapidly during the first 10 years of exposure. The time to peak of HFNIHL% depended on the noise level. For example, when the noise level was 85 to 90 dB(A), the time to peak of HFNIHL% was 15 years, and then decreased; when the noise level was above 90 dB(A), the time to peak was 20 years, and then decreased gradually. Figure 4B shows that HFNIHL% could develop for up to 20 years. The speed of HFNIHL% development with kurtosis >10 is higher than that with kurtosis<10 during the first 10 years of exposure. The two curves intersected when the exposure duration was greater than 10 years. When kurtosis was greater than 10, HFNIHL% increased from 5.55% to 32.19% during the first 10 years of exposure, with an average HFNIHL% of 24.77%. This average value was significantly higher than that (19.07%) when kurtosis was lower than 10. When the exposure duration was greater than 10 years, there was no significant difference in HFNIHL% between the two kurtosis groups ($p > 0.05$).

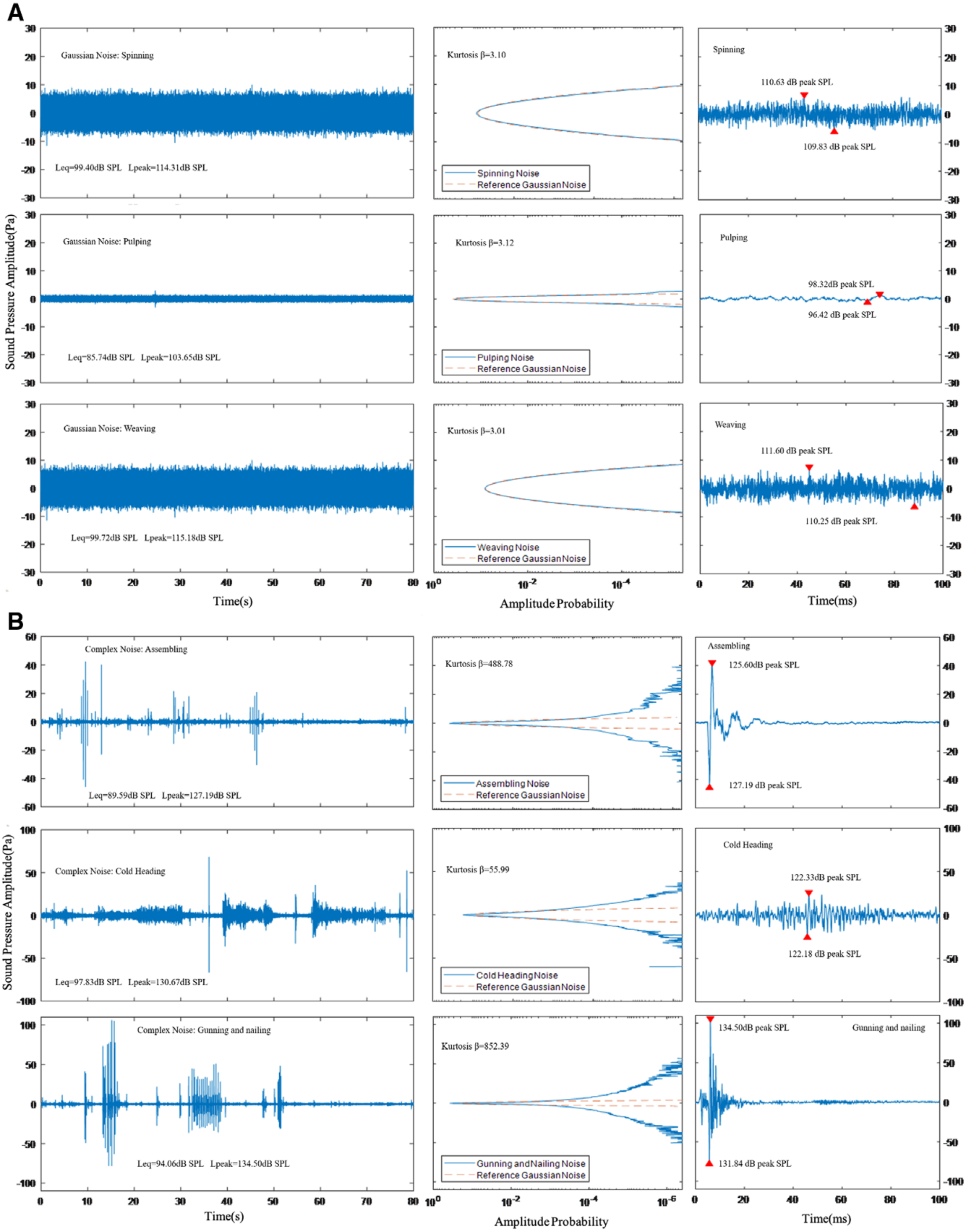


Fig. 1. Waveforms (left), amplitude probabilities (middle), and peak SPL distributions (right) from 13 typical industrial noises. (A) Spinning, pulping, and weaving; (B) assembling, cold heading, and nail gunning; (C) forging, metal processing, and woodworking; (D) polishing, punching, stamping; and (E) welding.

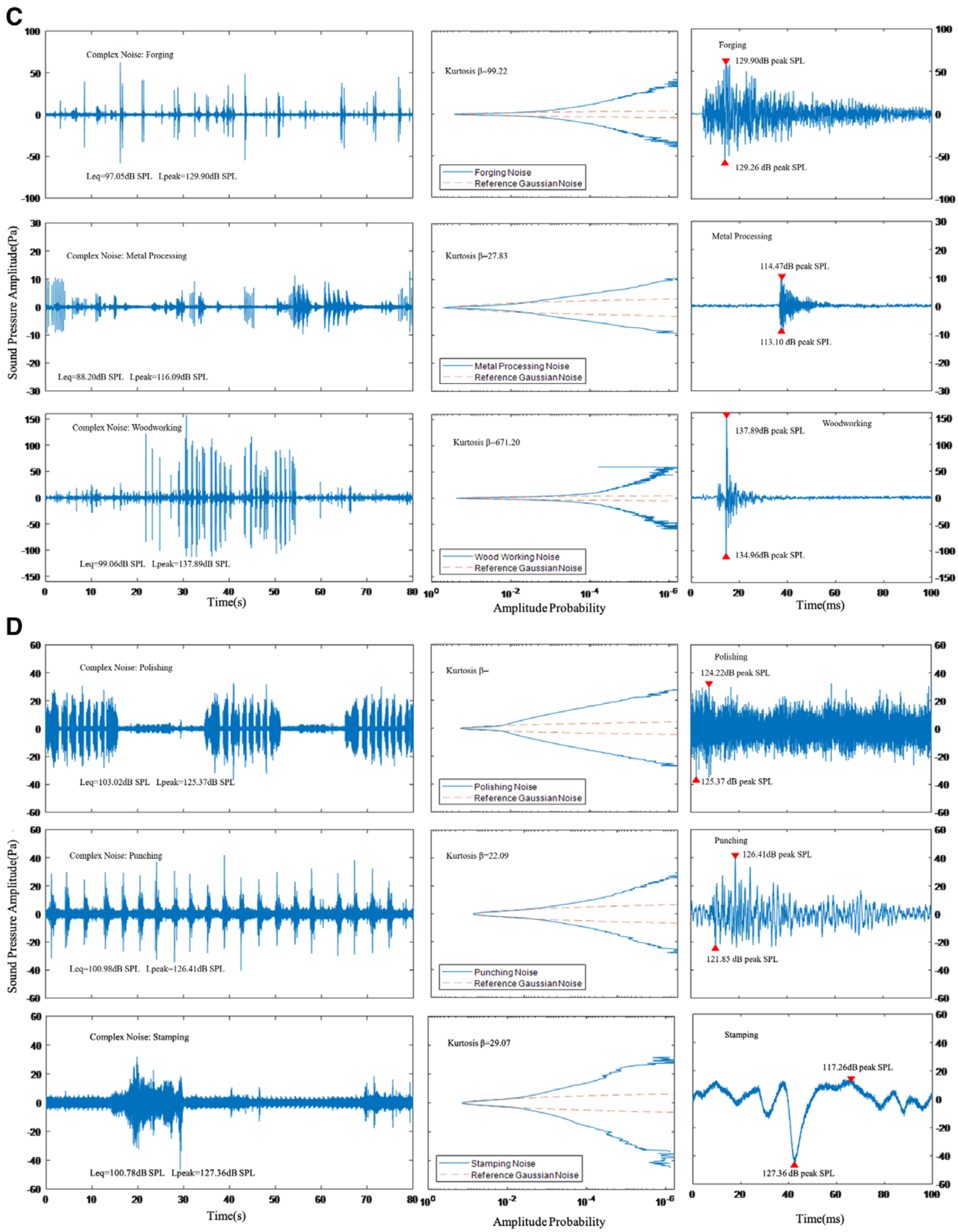


Fig. 1. Continued.

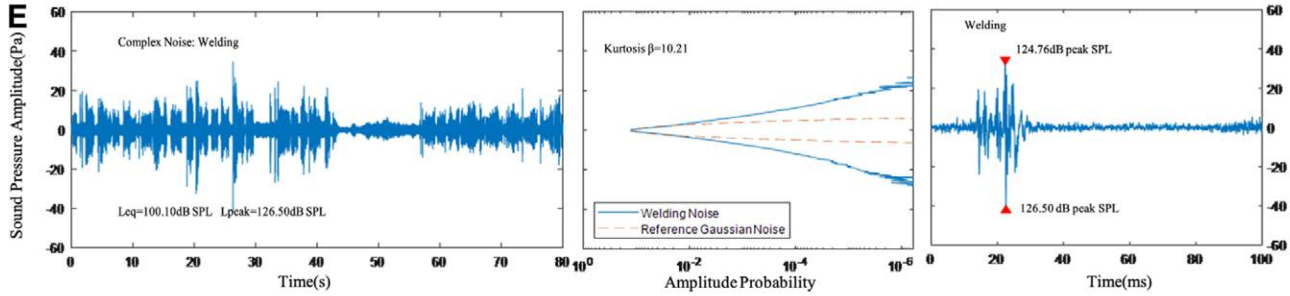


Fig. 1. Continued.

Figure 4C shows that HFNIHL% increased with kurtosis across the CNE levels and that there were significant differences in HFNIHL% among the kurtosis groups at each CNE level ($p < 0.05$ or $p < 0.01$). Figure 5 shows that HFNIHL% also increased with kurtosis across the $L_{Aeq.8h}$ levels and that there were significant differences in HFNIHL% between the kurtosis groups at each of the $L_{Aeq.8h}$ levels > 80 dB(A) ($p < 0.05$ or $p < 0.01$).

Safety Evaluation of the Occupational Exposure Limit of 85 dB(A) Based on Kurtosis • Figure 5 illustrates that the average HFNIHL% at $L_{Aeq.8h}$ between 80 dB(A) and 85 dB(A) was 24.80%, which was significantly higher than that at $L_{Aeq.8h} < 80$ dB(A) (10.13%; $p < 0.01$). When $L_{Aeq.8h}$ was 80 to 85 dB(A), the HFNIHL% at kurtosis > 100 was 34.15%, which was significantly higher than that at kurtosis between 10 and 100 (19.58%) or at kurtosis < 10 (13.75%; $p < 0.05$ and $p < 0.01$). When $L_{Aeq.8h}$ was lower than 80 dB(A), there was no difference in HFNIHL% among the kurtosis levels ($p > 0.05$).

DISCUSSION

This study applied kurtosis as an indirect metric of noise temporal structure to evaluate the hearing loss caused by both steady state and complex noise exposures. The results of this study highlight the importance of temporal characteristics in the assessment of NIHL.

Figure 1A and B demonstrates that a noise waveform of Gaussian or quasi-Gaussian shape was generated from specific noise activities, such as spinning, weaving, or pulping. These waveforms are flat, with mean kurtosis ≤10. In the manufacturing industry, The complex noise waveforms generated by most types of work, such as nail gunning, woodworking, cold heading, and metal processing, shared a common characteristic. These noises consist of a background Gaussian noise that is punctuated by a temporally complex series of randomly occurring high-level impulsive/impact noise transients. Their kurtosis values are larger than 10. Theoretically, the kurtosis of a Gaussian noise waveform is 3. However, the complexity of the noise environment, even when coming from a steady noise source, might lead to a higher kurtosis level of between 3 and 10 (Davis et al. 2012; Zhang et al. 2020). In other words, in a real working scenario, the noise measured from a steady source might belong to the quasi-Gaussian type. Therefore, a mean kurtosis of 10, rather than 3, could be recommended as the boundary between steady state and complex noise for field investigation. Our findings suggest that each type of work produces its own unique temporal waveform shape with a specific kurtosis. These results were supported by our preliminary investigation in the automotive industry, in which smelting, welding, grinding, and stamping activities generated their own unique noise temporal waveforms (Davis et al. 2009; Chen et al. 2019). Another study (Qiu et al. 2020) compared the waveforms and amplitude probabilities between the three types of industrial noises from spinning, stamping, and metalworking activities, and showed that the noise amplitude distributions with heavier tails have higher kurtosis values. In this study, more noise recordings with different kurtosis values were analyzed to further verify this result (as shown in Fig. 1).

Table 2 suggests that there is a specific level of noise intensity or kurtosis for each work type in the manufacturing industry. The lack of correlation between noise intensity and kurtosis indicates that their different properties (energy vs. structure) lend to them being mutually independent. Both Figure 1 and Table 2 suggest that the Gaussian and complex noise types could be identified based on a comprehensive evaluation of the work type, unique noise waveform shape, and specific kurtosis value.

Table 1 shows that 77.6% of the Chinese manufacturing workers from the six investigated industries were exposed to noise levels higher than 85 dB(A), with an average level of 89.43 ± 6.81 dB(A) and an average exposure duration of 9.15 ± 7.68 years. As many as 77.62% of the manufacturing workers were exposed to complex noise. As a result, 27.92% of them suffered from HFNIHL, with a mean $NIPTS_{346}$ of 24.16 ± 14.13 dB HL. These results suggest that the wide distribution of noise in manufacturing industries, high noise levels, long-term exposure to noise, and high noise temporal complexity are risk factors for NIHL. Our findings on the prevalence and characteristics of noise exposure and occupational NIHL in China are similar to those in other countries. In Iran, the average noise level of the occupational population reached 90.29 dB(A), with an overall hearing threshold of 26.44 ± 8.09 dB HL (Stucken & Hong, 2014). In South Korea, more than 90% of the evaluated workplace noise levels exceeded the OEL of 85 dB(A), and 92.9% of the suspected occupational diseases were occupational noise-induced deafness (Kim 2010). In the United States, 34% of the manufacturing workers were exposed to noise levels >85 dB(A) (Bolt et al. 1976), and approximately 15% of workers have experienced NIHL (Shargorodsky et al. 2010; Masterson et al. 2015).

In this study, the prevalence of NIHL among Chinese manufacturing workers showed that its principal characteristics are associated with noise energy and temporary structure, patterns of NIHL development, and noise OEL setting. Table 3 shows that the order of ORs for risk factors was as follows: $OR_{LAeq.8h} > OR_{kurtosis} > OR_{sex} > OR_{age} > OR_{duration}$, which suggests that $L_{Aeq.8h}$ has the highest contribution to NIHL, and kurtosis, exposure duration, age, and sex, are important factors influencing NIHL. The multiple linear regression analysis demonstrated that among these risk factors, $L_{Aeq.8h}$, kurtosis, and exposure duration had

TABLE 2. Noise levels and kurtosis values for some typical types of work in manufacturing industry

			$L_{Aeq.8h}$ [dB(A)]	Kurtosis *	NIPTS$_{346}$ (dB)		Difference of L_{peak} minus $L_{Aeq.8h}$	
Noise type	Industry	Type of work	Mean ± SD	Mean ± SD	Mean	Range		Kurtosis†
Gaussian noise	Textile	Spinning	95.33 ± 9.29	10.00 ± 11.17	32.13	0–86	14.91	3.10
		Weaving	95.76 ± 3.33	8.08 ± 12.44	25.17	3–67	15.46	3.01
	Papermaking	Pulping or rewinding	89.15 ± 4.34	9.32 ± 6.66	24.18	0–60	17.91	3.12
Complex noise	Furniture	Nail gunning	89.12 ± 4.42	246.37 ± 172.80	28.90	3–76	40.44	852.39
		Woodworking	88.34 ± 3.89	89.66 ± 79.74	27.60	4–79	38.83	89.66
	Automobile, metal product, general equipmenft	Cold heading	88.40 ± 3.10	12.99 ± 13.05	23.03	1–60	32.84	55.99
		Metal processing	89.84 ± 5.41	50.84 ± 54.06	46.78	7–78	27.89	27.83
		Assembling	89.68 ± 5.53	46.24 ± 86.24	49.38	13–78	37.60	488.78
		Welding	91.18 ± 5.42	42.17 ± 48.14	41.92	13–73	26.40	12.21
		Stamping	92.98 ± 5.10	42.17 ± 48.15	47.38	13–90	26.58	29.07
		Polishing or grinding	91.94 ± 5.79	23.03 ± 30.01	45.58	9–66	22.35	9.69
		Punching	92.05 ± 2.15	17.98 ± 11.21	51.12	40–69	25.43	22.09
		Forging or casting	92.71 ± 7.08	37.64 ± 34.24	54.35	40–79	32.85	99.22

NIPTS$_{346}$, noise-induced permanent threshold shift at 3, 4, and 6kHz frequencies.
**The mean kurtosis was calculated based on a shift-long noise recording.*
†The kurtosis value calculated from an 80-s noise waveform in Figure 1 was significantly associated with the difference of peak SPL (L_{peak}) minus its $L_{Aeq.8h}$ (p < 0.01).
NIPTS, noise-induced permanent threshold shift.

greater effects on NIPTS than age or sex. Each of these risk factors could play an important role in the prevalence of NIHL. Age and sex contribute significantly to the HFNIHL%, even though the hearing thresholds were already adjusted by these two factors based on Annex B Table B.3 in the ISO 1999 (2013).

Figure 2 shows that there is a linear relationship between CNE, exposure time, noise level or kurtosis, and HFNIHL%, indicating a significant dose-response relationship between these factors and HFNIHL%. Figure 2A and B illustrates that after CNE was adjusted by kurtosis, the linear equation between HFNIHL% and kurtosis-adjusted CNE for complex noise almost overlapped the linear equation between HFNIHL% and CNE for Gaussian noise. Furthermore, Table 2 shows that there is a statistically significant correlation between the kurtosis measure and the abrupt growth level of peak SPL in different types of work in the manufacturing industry (p < 0.01). These results suggest that the kurtosis measure can well quantify the complexity of the noise signal. Müller et al. (2020) applied kurtosis to quantify the complexity of impulsive underwater sounds and provided several practical formulas for kurtosis calculation.

The order of R^2 was as follows: $R^2_{CNE} > R^2_{duration} > R^2_{LAeq.8h} > R^2_{kurtosis}$. Note that the CNE is a comprehensive energy indicator that combines the exposure duration and noise level. These results further indicate that noise energy was the major determinant of NIHL development; however, noise energy alone was insufficient when evaluating the hazard caused by complex noise exposure. The temporal structure of noise exposure (i.e., kurtosis) also played an important role in NIHL evaluation that should not be ignored.

Figure 2B shows that the prevalence of HFNIHL (>20.38%) among manufacturing workers exposed to complex noise with kurtosis >10 was significantly higher than that in workers exposed to Gaussian noise with kurtosis <10 (13.52%; p < 0.05), suggesting that workers exposed to complex noises had greater hearing loss than those exposed to Gaussian noise. This result emphasizes that, in addition to noise energy indicators such as noise intensity and exposure duration, the temporal structure of noise, as indicated by kurtosis, is also an important risk factor for NIHL. Several animal experiments (Hamernik et al. 2003, 2007; Qiu et al. 2006, 2013) and epidemiologic studies (Davis et al. 2009; Zhao et al. 2010; Xie et al. 2016) have demonstrated that the current international standards for noise exposure underestimate the hearing trauma from complex noise; noise energy is a necessary metric, but the structure characteristic of complex noise is also an important factor when evaluating hearing loss induced by complex noise.

Figure 3A shows the mean NIPTS curves of the left and right ears overlapping at the test frequencies. This overlap is not affected by changes in noise energy or temporal structure, suggesting that the effects of noise exposure on binaural hearing are symmetric. Figure 3A shows a "V" shape with a notch at a frequency of 4kHz, which recovered at the frequency of 8kHz. The notched audiogram refers to a "notching" of the audiogram at the high frequencies of 3, 4, or 6kHz with recovery at 8kHz. NIHL preferentially affects the high frequencies, with hearing loss beginning characteristically around 4kHz before spreading to the lower frequencies as the 4kHz loss progresses. The audiometric notch at 4kHz is a clear clinical sign and might be valuable in the diagnosis of NIHL (Coles

TABLE 3. Regression analysis of key factors influencing NIHL in manufacturing workers (n = 3102)

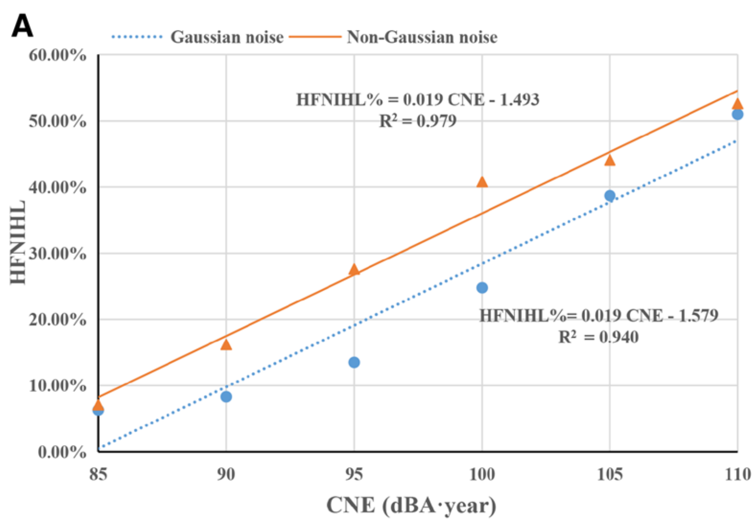
	Binary logistic regression analysis*			Multiple linear regression analysis†	
Factor	B	p	OR (95% CI)	t	p
Sex	0.25	<0.05	1.28 (1.05–1.56)	0.10	>0.05
Age (yr)	0.20	<0.01	1.23 (1.11–1.36)	1.21	>0.05
Exposure duration (yr)	0.14	<0.01	1.15 (1.08–1.24)	4.05	<0.01
$L_{Aeq.8h}$ [(dB(A)]	0.37	<0.01	1.44 (1.34–1.55)	12.26	<0.01
Kurtosis	0.28	<0.01	1.33 (1.20–1.47)	7.32	<0.01

Age (years): <30, ~40, ~50, ~60, ~70, ≥70; Exposure duration (years): <5, ~10, ~15, ~20, >20; Kurtosis: < 10, ~50, ~100, >100; $L_{Aeq.8h}$ [(dB(A)]: <80, ~85, ~90, ~95, ~100, ≥100; Sex: male/female.
**HFNIHL% as a categorical dependent variable.*
†NIPTS as a continuous dependent variable.
HFNIHL, high-frequency noise-induced hearing loss; NIHL, noise-induced hearing loss; NIPTS, noise-induced permanent threshold shift.

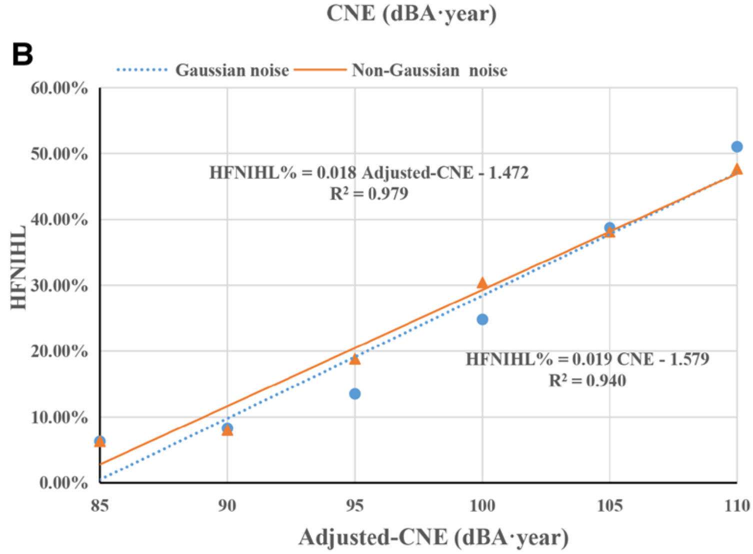
et al. 2000). The results from chinchilla studies (Harding & Bohne 2009) showed that 4-kHz octave band of noise could produce greater NIPTS especially for outer hair cell damage than 0.5 kHz octave band of noise, suggesting the chinchilla cochlea is more sensitive to high-frequency noise, especially at 4 kHz. The chinchilla animal model supports the results shown in Figure 3 because the chinchilla's auditory system is very similar to that of humans (Trevino et al. 2019). Moreover, it can be seen from Figures 3B and C that the hearing loss notch degree at the high frequencies (3 to 6 kHz) deepens with the increase of L_{Aeq} and kurtosis, and reaches the maximum at 4 kHz. This notch pattern indicates that both noise level and temporal structure could aggravate the development of NIHL at high frequencies. The notch audiogram also indicates that hearing loss in the high frequencies is more severe than at low frequencies. This finding agrees with relevant reports that noise exposure alone can produce a hearing loss of up to 75 dB in high frequencies; however, it rarely produces a loss greater than 40 dB at lower frequencies (Dobie 2015).

Figure 4A–C) illustrates several NIHL development patterns in association with noise temporal structure or energy. Figure 4A shows that the prevalence of HFNIHL among workers increased most rapidly during the first 10 years of exposure to industrial noise, reached the peak after 15 to 20 years of exposure, and then decelerated as the worker's hearing threshold increased to a certain level. This result is in agreement with NIHL characteristics, as described by the American College of Occupational and Environmental Medicine (Durch et al. 2005; ACOEM 2018). For example, hearing loss due to continuous or intermittent noise exposure increases most rapidly during the first 10 to 15 years of exposure, and the rate of hearing loss subsequently decelerates as the hearing threshold increases. Figure 4A further demonstrates that the time to reach the peak depends on the noise level. That is, the higher the noise level, the later the peak time. This finding might supplement the earlier opinion from the ACOEM.

Figure 4B shows that HFNIHL among manufacturing workers could develop for up to 20 years. The prevalence of HFNIHL during the first 10 years of exposure to complex noise (24.77%)



CNE (dBA·year)	HFNIHL		
	Gaussian	Non-Gaussian	Difference
85	6.30%	7.10%	0.80%
90	8.30%	16.20%	7.90%
95	13.50%	27.60%	14.10%
100	24.80%	40.80%	16.00%
105	38.70%	44.10%	5.40%
110	51.00%	52.60%	1.60%
Average	23.77%	31.40%	7.63%



Adjusted CNE (dBA·year)	HFNIHL		
	Gaussian	Non-Gaussian	Difference
85	6.30%	6.30%	0.00%
90	8.30%	8.00%	-0.30%
95	13.50%	18.80%	5.30%
100	24.80%	30.40%	5.60%
105	38.70%	38.10%	-0.60%
110	51.00%	47.70%	-3.30%
Average	23.77%	24.88%	1.12%

Fig. 2. A linear relationship between HFNIHL% and CNE (or adjusted CNE), kurtosis, $L_{Aeq.8h}$, or exposure duration (ED). (A) The linear regression equation between HFNIHL% and CNE for complex noise and Gaussian noise. (B) The linear regression equation between HFNIHL% and adjusted CNE for complex noise, which is almost overlapped with that of Gaussian noise; (C) The linear regression equation between HFNIHL% and kurtosis when CNE < 100; (D) The linear regression equation between HFNIHL% and $L_{Aeq.8h}$; (E) The linear regression equation between HFNIHL% and exposure duration. CNE, cumulative noise exposure; HFNIHL, high-frequency noise-induced hearing loss.

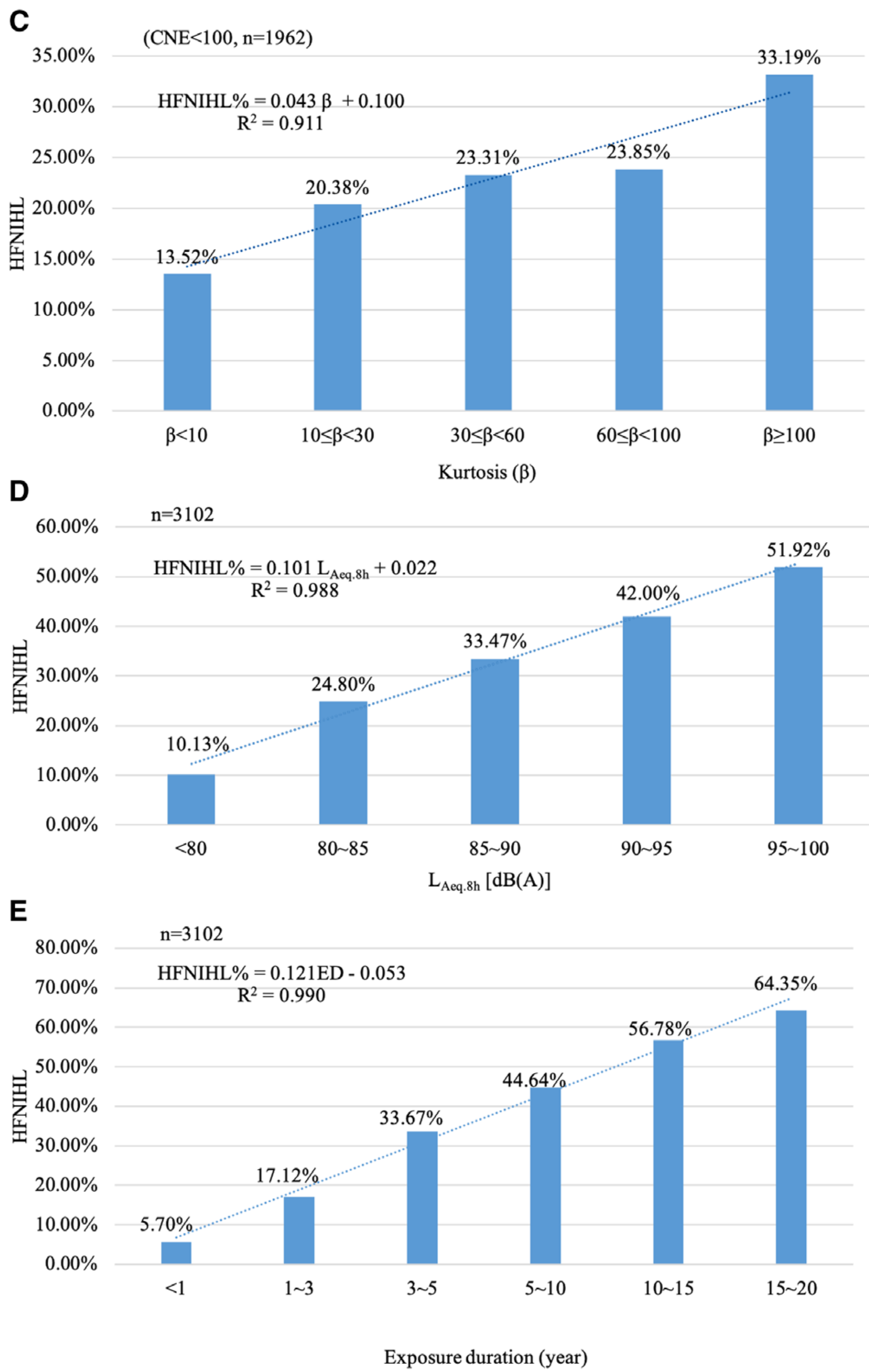


Fig. 2. Continued.

was significantly higher than that of Gaussian noise exposure (19.07%; $p < 0.05$). Moreover, in the complex noise environment, the development speed of NIHL in the first three years is faster than in the Gaussian noise environment. These findings suggest that during the first 10 years of exposure, and particularly during the first three years, complicated temporal noise structure accelerates the development of NIHL and contributes to a higher prevalence of hearing loss. After 10 years of noise exposure, the intersection point of HFNIHL% caused by complex noise and Gaussian noise indicates that the influence of noise temporal structure on NIHL decreases with the increase of exposure time. These findings might improve our understanding of NIHL development patterns for different exposure durations suggested by the ACOEM.

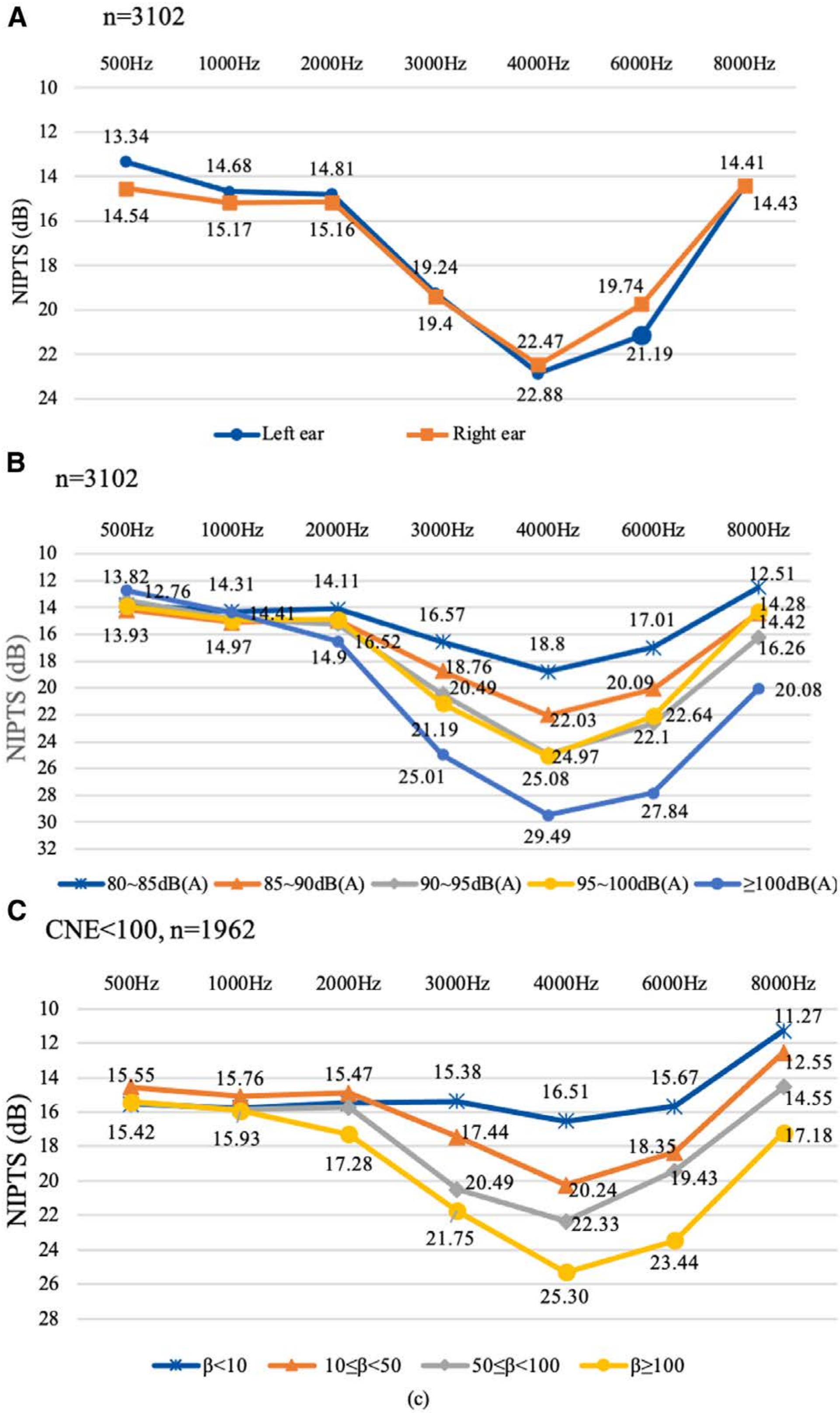


Fig. 3. Symmetry and notching of NIHL associated with kurtosis. (A) Overlapped NIPTS curves for the left and right ears and their 'V' shape notch at high frequencies; (B) The notch of high-frequency hearing loss was deepened with the increase of $L_{Aeq.8h}$; (C) The notch of high-frequency hearing loss was deepened with the increase of kurtosis. NIHL, noise-induced hearing loss. NIHL, noise-induced hearing loss; NIPTS, noise-induced permanent threshold shift.

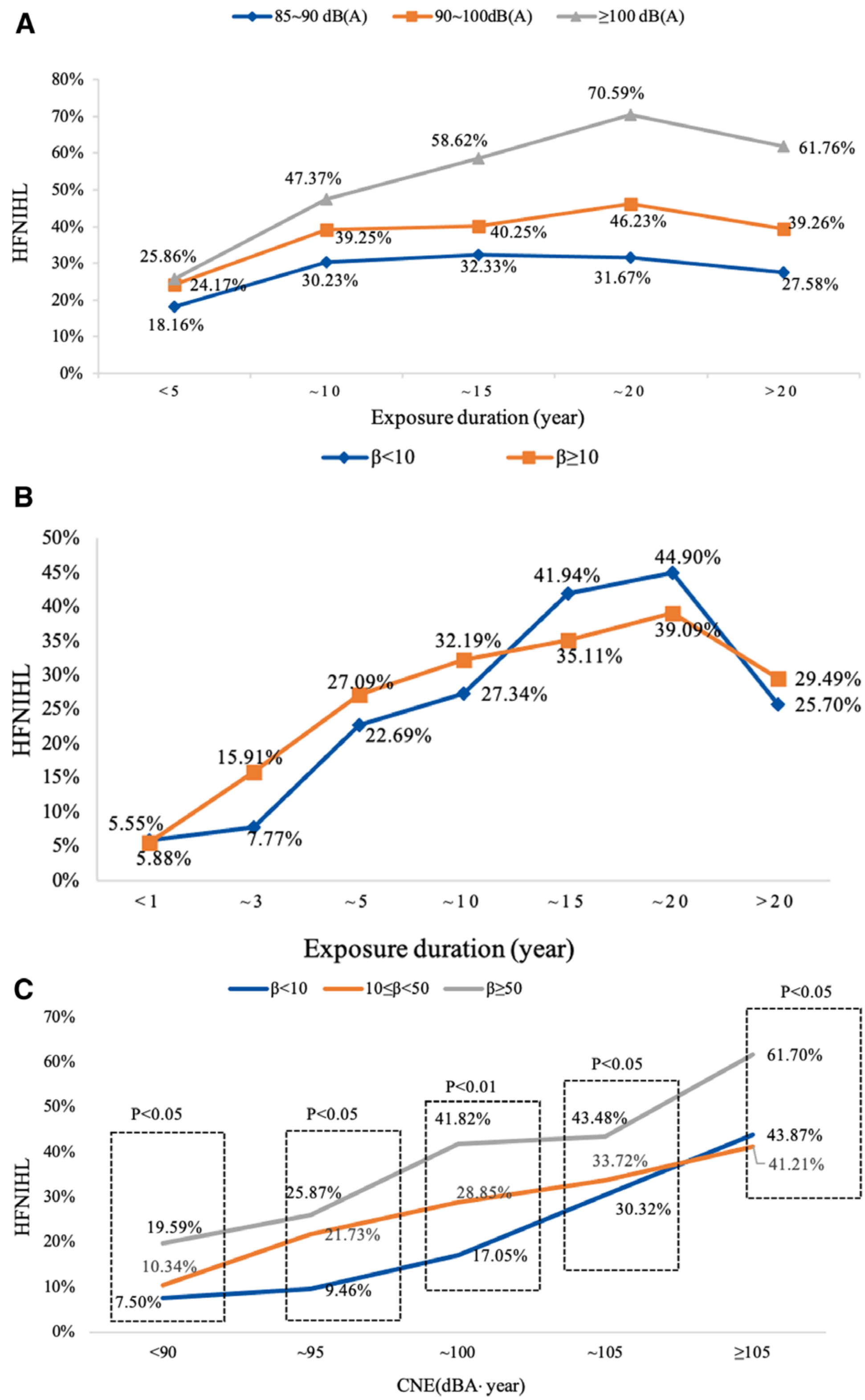


Fig. 4. Patterns of NIHL development in association with exposure duration, noise level, and kurtosis. (A) HFNIHL% increased more rapidly during the first 10 years of exposure when $L_{Aeq.8h}$ > 85 dB(A), and the time to peak of HFNIHL% depended on the noise level; (B) HFNIHL% could develop for up to 20 years. During the first 10 years of exposure, the curve of HFNIHL% development with kurtosis > 10 was higher than that with kurtosis <10; (C) HFNIHL% increased with kurtosis across the CNE levels, and there were significant differences in HFNIHL% among the kurtosis groups at each CNE level. CNE, cumulative noise exposure; HFNIHL, high-frequency noise-induced hearing loss; NIHL, noise-induced hearing loss.

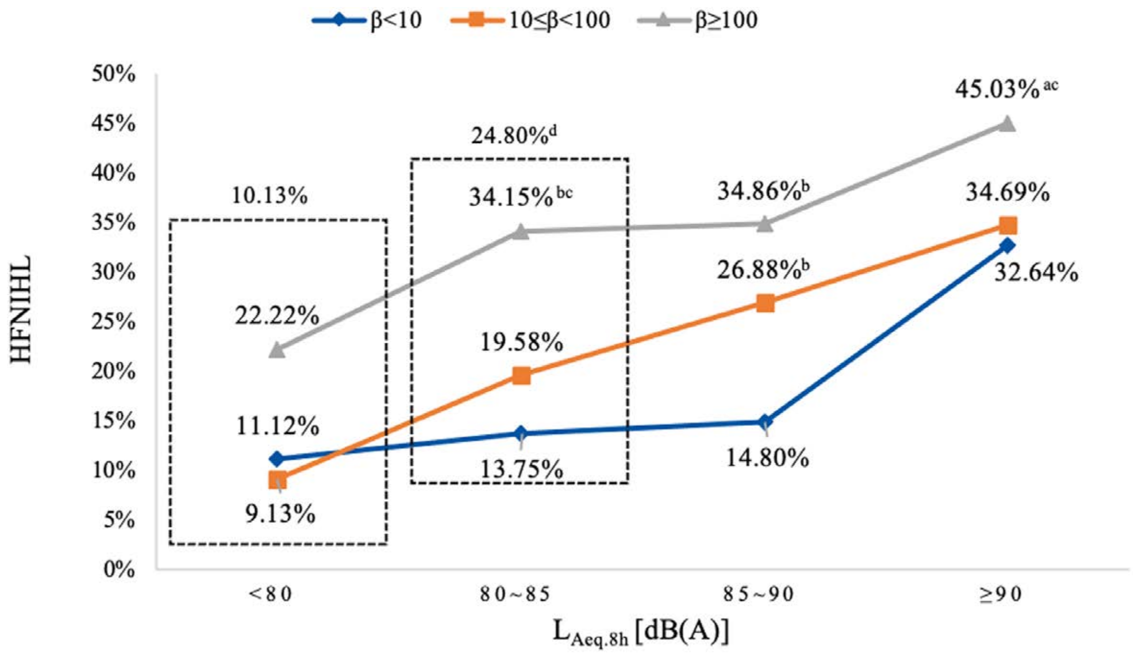


Fig. 5. Safety evaluation of the occupational exposure limit of 85 dB(A) based on kurtosis. The average HFNIHL% (24.80%) at 80 ≤ $L_{Aeq.8h}$ <85 dB(A) was significantly higher than that (10.13%) at $L_{Aeq.8h}$<80 dB(A) (p < 0.01). When $L_{Aeq.8h}$ was 80–85 dB(A), the HFNIHL% (34.15%) at kurtosis > 100 was significantly higher than that (19.58%) at 10<kurtosis ≤100 or that (13.75%) at kurtosis ≤10. [a]p < 0.05, as compared with the group with kurtosis <10; [b]p < 0.01, as compared with the group with kurtosis <10; [c]p < 0.05, as compared with the group with 10 ≤ kurtosis <100; [d]p < 0.01, as compared with the group with $L_{Aeq.8h}$<80 dB(A). HFNIHL, high-frequency noise-induced hearing loss.

Figure 4C shows that the prevalence of NIHL increased significantly with kurtosis at each CNE level ($p < 0.05$ or $p < 0.01$), which further supports the separate effect of noise temporal structure on NIHL prevalence when controlling for the CNE effect. Furthermore, Figure 4C shows that exposure to noise with a highly complex temporal structure (e.g., kurtosis > 50) had a significant effect on workers' hearing loss and could lead to a higher prevalence of NIHL in the exposed occupational population.

Figure 5 illustrates that the prevalence of NIHL among workers exposed to industrial noise at a level of 80 to 85 dB(A) was 24.80%, with an average exposure duration of 9.15 ± 7.68 years. This NIHL rate is significantly higher than that of workers exposed to a noise level < 80 dB(A) (10.13%; $p < 0.01$). This difference suggests that workers are at high risk of hearing loss from long-term exposure to industrial noise of 80 to 85 dB(A). It may therefore be assumed that the noise OEL of 85 dB(A) may be unsafe for the hearing of the manufacturing worker. Figure 5 further shows that the prevalence of NIHL among workers exposed to an industrial noise level of 80 to 85 dB(A) with a high kurtosis (β > 100) was significantly higher than that among workers exposed to the same noise level with kurtosis < 100. This finding indicates that the uncertainty of the OEL of 85 dB(A) might be related to noise exposure with a complex temporal structure. The ACOEM had also concluded that although the Occupational Safety and Health Administration action level for noise exposure is 85 dB, there is evidence that noise exposure between 80 dB and 85 dB might cause hearing loss in abnormally susceptible individuals. There is also evidence that the NIHL risk increases with long-term exposure to noise above 80 dB and that the risk increases significantly as the exposure rises above 85 dB (ANSI, American National Standard Institute 1996). Therefore, the OEL for noise should be modified based on the noise temporal structure. For example, the OEL of 85 dB(A) might be reduced to 80 dB(A) for occupational populations exposed to noise with a high kurtosis value. Further studies are needed to determine the detailed OEL for noise based on the noise temporal structure.

One limitation of this study is that the sample size for some types of work (e.g., punching, forging, and casting) is insufficient to make them unrepresentative. To validate the results, the overall sample size from different industries needs to be further expanded. Another limitation to note is that the kurtosis measure is a proxy measure for quantifying noise complexity and may be limited to quantifying certain aspects of a complex signal. Only when kurtosis is combined with energy can kurtosis play a greater role in the evaluation of NIHL. In addition, given the complexity of industries and their production processes, there might be a small amount of co-exposure to noise and ototoxic solvents or heavy metals in some jobs, which may influence the hearing outcomes.

CONCLUSION

On the basis of the above findings, the following conclusions can be drawn: (1) The noise type could be identified by comprehensive evaluation of the work type, noise waveform, and kurtosis value; (2) In the evaluated industries, about 27.9% of Chinese manufacturing workers are developing HFNIHL, and 77.6% are exposed to complex and harmful noise levels; (3) In the evaluation of hearing loss caused by complex noise, not only noise energy but also the temporal structure of noise should be considered. Kurtosis of noise can provide an indirect measure sensitive to the presence of impulsive components in complex noise exposure, and can be used to quantify the risk of NIHL; (4) It is necessary to re-evaluate the safety of permissible exposure limit of 85 dB(A) as noise with high kurtosis value can aggravate or accelerate early NIHL. Additional efforts are needed to reduce noise exposure among workers in the manufacturing industries.

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M.B. Zhang designed and performed investigation, analyzed data, and wrote the original draft; H.W. Xie, Z.H. Shi, X.J. Gao, L.F. Zhou, and H. Zou conducted field investigation, subject selection and interview, data evaluation, and quality control; X.H. Xu and W.J. Hu designed investigation and provided the discussion; W. Qiu and X. Sun designed and supervised the project, analyzed data, wrote, and edited the article. All authors discussed the results and implications and commented on the article at all stages. There are no conflicts of interest, financial, or otherwise.

Address for correspondence: Xin Sun, PhD, National Institute of Occupational Health and Poisoning Control, Beijing 100051, China. E-mail: sunxin@niohp.chinacdc.cn or Wei Qiu, PhD, Auditory Research Laboratory, State University of New York at Plattsburgh, 101 Broad Street, Plattsburgh, NY 12901, USA. E-mail: qiuw@plattsburgh.edu

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