Occupational Hearing Loss Associated With Non-Gaussian Noise: A Systematic Review and Meta-analysis

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Objectives: Epidemiological characteristics of occupational noise-induced hearing loss (NIHL) associated with non-Gaussian noise are still unclear and have been rarely reported in the literature.

Methods: The relationships between non-Gaussian noise exposure and occupational NIHL were analyzed based on the published papers. Systematic review and meta-analysis of epidemiological studies were performed.

Results: Of 78 epidemiological studies (47,814 workers) selected, there were seven cohort studies and 71 cross-sectional studies. The incidence of high-frequency NIHL (HFNIHL) and speech-frequency NIHL (SFNIHL) in the seven cohort studies was 10.9 and 2.9%, respectively. In 71 cross-sectional studies, the prevalence of HFNIHL and SFNIHL was 34.2 and 18.9%, respectively. The average hearing threshold level at the high frequencies was 42.1 ± 17.4 dB HL. Workers exposed to non-Gaussian noise had a higher risk of developing HFNIHL than those not exposed to noise (overall-weighted odds ratio [OR] = 4.46) or those exposed to Gaussian noise (overall-weighted OR = 2.20). The Chi-square trend test demonstrated that the prevalence of HFNIHL was positively correlated with age, cumulative noise exposure, and exposure duration ($p < 0.001$).

Conclusions: Workers exposed to non-Gaussian noise suffered from greater NIHL than those exposed to Gaussian noise or not exposed to noise. Age, exposure duration, noise level, and noise temporal structure were the main risk factors for occupational NIHL. The A-weighted equivalent continuous sound pressure level (L_{Aeq}) is not a sufficient measurement metric for quantifying non-Gaussian noise exposure, and a combination of kurtosis and noise energy metrics (e.g., L_{Aeq}) should be used. It is necessary to reduce the exposure of non-Gaussian noise to protect the hearing health of workers.

Key words: Non-Gaussian noise, Complex noise, Hearing loss, Kurtosis, Occupational exposure, Systematic review.

INTRODUCTION

Hearing loss is reported as the most prevalent sensory disability worldwide. Noise is one of the most common risk factors for hearing loss. Worldwide, noise-induced hearing loss (NIHL) is a global public health problem, and occupational NIHL accounts for 7 to 21% of adults with disabling hearing loss (Nelson et al. 2005). For instance, occupational NIHL has the highest prevalence of occupational diseases in the United States (Themann et al. 2013). In 1995, a household survey in the United Kingdom showed that occupational NIHL accounted for 8% of all work-related illnesses (Jones et al. 1998). In China, noise-induced deafness has been the second most frequently reported occupational diseases in recent years, ranking behind pneumoconiosis (the top one occupational disease). The prevalence of occupational NIHL among noise-exposed workers in China was reported to be above 20% (Li et al. 2014).

With the development of the industrial economy, industrial noise sources have become more and more complex. The main type of noise produced from the industrial noise sources is non-Gaussian noise (also known as complex noise) rather than Gaussian noise (also known as steady state noise). Steady state noise often occurs during the spinning and weaving processes in textile mills and during the pulping process in paper-making mills (Suter 2017). Impulsive noise is defined as short duration but high-intensity noise generated by pressure release (impulse noise) or from the collision of solid objects (impact noise). Impulse noise is often military-related, with the peak noise level usually exceeding 140 dB(A). In contrast, impact noise generated in industries is usually accompanied by background noise with a high-peak noise level not usually exceeding 140 dB and a relatively long impulse duration (Ding 1992). Impact noise often occurs in industries with such work as hammering, stamping, forging, and riveting. Non-Gaussian noise comprises transient high-energy impulsive noise superimposed on the steady state background noise, and it is a sum of many noise types, including impulse noise, impact noise, and intermittent noise, except Gaussian noise (Suter 2017).

The generation of non-Gaussian noise is related to the inherent acoustic characteristics of noise sources, the features of the acoustic environment, and sound attenuation. Varying noise sources exist in the workplace; some generate steady state noise while others generate impulsive noise. Noises intertwine and react with each other, propagate through the air or solid objects, and are absorbed and reflected by the floor, walls, ceiling, and machinery surfaces in the workplace, leading to reverberation. The noise frequency spectrum and noise level can be modified depending on whether the acoustic environment is a free field, quasi-free field, or reverberant field (Suter 2017).

As reported in many animal experiments (Ahroon et al. 1993; Hamernik and Qiu 2001; Hamernik et al. 2003; Qiu et al. 2006, 2007) and some epidemiological studies (Seixas et al. 2012; Zhang et al. 2012), because of its complex temporal structure, non-Gaussian noise causes more significant hearing loss than

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Gaussian noise. These results indicate that NIHL is associated with energy and temporal structure of noise. The effect of noise temporal structure on NIHL greatly challenges the appropriateness of the existing international noise exposure standards (e.g., ISO 1999, 2013) for non-Gaussian noise, in which the noise energy (e.g., the A-weighted equivalent sound pressure level, L_{Aeq}) serves as the sole metric when evaluating NIHL based on the equal energy hypothesis. The equal energy hypothesis assumes that the cochlear impact of noise exposure is proportional to the exposure duration multiplied by the noise intensity, implying that hearing loss is independent of the acoustic energy temporal distribution. Thus, occupational NIHL associated with non-Gaussian noise might be underestimated with the existing standards regarding noise exposure measurement and risk assessment of hearing loss.

The direct reason for the underestimation may be the absence of practical approaches for quantifying the non-Gaussian noise exposure and evaluating the risk of hearing loss. The underlying reason may be more of a lack of understanding of the exposure characteristics of non-Gaussian noise and its relationship to occupational NIHL. Furthermore, the epidemiological characteristics of occupational hearing loss related to non-Gaussian noise are unclear, and the relevant literature is limited. This systematic review and meta-analysis aimed to analyze the relationship between occupational NIHL and non-Gaussian noise exposure and identify its key risk factors. The findings of this review can provide the basis for the early prevention and control of occupational hearing loss caused by non-Gaussian noise exposure and the formulation and implementation of related hearing loss prevention programs.

MATERIALS AND METHODS

Literature Retrieval

The Chinese literature databases searched were the China National Knowledge Infrastructure (CNKI, www.cnki.net), Chinese Sci-tech Journal Database (www.cqvip.com), and Wanfang database (www.wanfangdata.com.cn). The English literature databases searched were PubMed and Web of Science. The keywords used in the search were "complex noise," "occupational noise," "industrial noise," "non-Gaussian noise," "intermittency noise," "impact noise," "impulsive noise," "hearing loss," and "permanent threshold shift." In addition, the "literature retrospective method" was used to select the studies that met the inclusion criteria from previous reviews on non-Gaussian noise or Gaussian noise.

Inclusion and Exclusion Criteria

In this review, studies on occupational hearing loss associated with non-Gaussian noise were included. The inclusion criteria were as follows:

1. Studies with subjects engaged in industries such as, but not limited to, manufacturing, construction, mining, and electricity.
2. Studies whose subjects had a clear non-Gaussian noise exposure history. At least one of the following three conditions should have been met to determine whether these subjects were exposed to non-Gaussian noise:
   2a. Studies that clearly state that the subjects were exposed to either non-Gaussian noise, complex noise, impulsive noise, or impact noise;
   2b. Studies that use kurtosis as one of the noise metrics. Kurtosis is a statistical metric that can reflect the extent to

which a variable's distribution deviates from the Gaussian distribution. The mean kurtosis ≥10 or median kurtosis ≥4 (Davis et al. 2009) were used to characterize non-Gaussian noise. Since the probability density function of steady state noise obeys a normal distribution (Gaussian distribution), kurtosis could reflect the impulsiveness of the noise. Noise exhibiting a higher kurtosis metric would contain a greater amount of impulsiveness.
   2c. Studies that have similar job duties. If study subjects were in similar job duties with those workers in the studies meeting the above two conditions, it could be considered that they were likely exposed to non-Gaussian noise.
   As a contrast, Gaussian noise exposure should meet at least one of the following conditions: (a) studies have clearly stated that the subjects were exposed to either Gaussian noise or steady state noise; (b) mean kurtosis of noise was reported to be less than 10 or median kurtosis was less than 4.
3. Studies where the definition of NIHL matched our definition. Different definitions of high-frequency NIHL (HFNIHL) mentioned in selected studies from different countries were adopted for this review. Internationally, the definitions for HFNIHL were usually defined as an average hearing threshold ≥25 dB HL at high frequencies of 3, 4, and 6 kHz, or the hearing threshold ≥30 (or 25) dB HL at any high frequency (3, 4, 6, or 8 kHz). In addition, the definition of HFNIHL from China was also adopted, which was defined as an average hearing threshold of ≥40 dB HL at 3, 4, and 6 kHz based on an occupational health standard in China (i.e., diagnosis of occupational noise-induced deafness, GBZ49 2014). In this review, the speech-frequency NIHL (SFNIHL) was defined as the average hearing threshold in the better ear of ≥26 (or 20) dB HL at speech frequencies (0.5, 1, and 2 kHz).

The exclusion criteria were as follows:

1. Studies on the engineering or theoretical models related to NIHL;
2. Studies on the clinical treatment of NIHL;
3. Cytological and genetic studies on the mechanism of hearing loss induced by noise;
4. Animal experiments regarding noise exposures and auditory or nonauditory damage;
5. Studies in which the prevalence of NIHL was calculated with the number of ears, instead of the number of study subjects;
6. Studies in which the subjects self-reported their hearing status;
7. Studies in which the subjects were engaged in the music and transportation industries or were exposed to military-related noise;
8. Studies on nonauditory system injuries attributed to noise exposure in human;
9. Studies on co-exposure to noise and other harmful factors;
10. Books, reviews, conference papers, and news articles on noise.

Data Analysis and Extraction

EndNote, which served as the software of reference management, was used for managing literature and extracting the information on study design, author, industry, job duties (types of work), noise exposure, study subjects, use of hearing protection

devices (HPDs), and hearing loss for this systematic review and meta-analysis. General information on the subjects (e.g., age) and noise exposure factors (e.g., exposure duration, L_{Aeq}, cumulative noise exposure [CNE], and kurtosis) were presented as mean ± SD or range (minimum–maximum). The proportion of male workers, the incidence of NIHL, or the prevalence of NIHL were presented as percentages (%). Use of HPDs was divided into four grades: not mentioned, no use (none of the subjects in the included study were reported to use HPDs), rarely used (fewer than 50% of subjects in the included study were reported to use HPDs), and regularly used (not fewer than 50% of subjects in the included study were reported to use HPDs).

CNE, a composite noise exposure index (Xie et al. 2016), was used to quantify the noise exposure for each subject. The CNE is defined as:

$$CNE = 10\log\left[\frac{1}{T_{ref}}\sum_{i=1}^{n}(T_i \times 10^{L_{Aeq,8h}/10})\right]$$

In the formula, T_i, exposure duration in years; $L_{Aeq,8h}$, equivalent continuous A-weighted noise exposure level in decibels normalized to an 8-hour working day; n, types of noise that the worker has ever been exposed to; T_{ref}, 1 year.

To conduct the meta-analysis for the cross-sectional studies with control groups, the weighted mean difference and its 95% confidence interval (95% CI), as the metrics of combined effect size, were used for characterizing continuous variables (i.e., age, exposure duration, L_{Aeq}, CNE, and kurtosis), while overall-weighted odds ratio (OR) and its 95% CI were used for characterizing categorical variables (i.e., the prevalence of NIHL and the proportion of male workers). The fixed-effect model was adopted for the analysis when data from the different studies were homogeneous ($p > 0.01$ and $I^2 \leq 50\%$ based on the heterogeneity test); otherwise, the model was replaced by the random-effect model. Subgroups were designed for age, sex, exposure duration, and L_{Aeq} to analyze their ORs of HFNIHL. A trend Chi-square test was conducted to verify the dose-response relationship between key factors (e.g., age, exposure duration, and CNE) and the prevalence of HFNIHL. A probability level of $p < 0.05$ was considered statistically significant.

A total of 348 studies were initially included in this study based on the literature retrieval and retrospective review, and 246 studies were excluded after examining the title or abstract based on the exclusion criteria. Of the remaining studies, 24 articles were further excluded after reviewing the full text. Finally, 78 studies were included in this study. The literature screening process is shown in Supplemental Data File 1 http://links.lww.com/EANDH/A807.

RESULTS

The 78 articles in this review included seven cohort studies and 71 cross-sectional studies, of which 15 cross-sectional studies were with a non-noise exposure group as controls and 30 with a Gaussian noise exposure group as controls.

Cohort Studies

Table 1 shows the seven cohort studies that dynamically investigated the hearing loss of workers exposed to non-Gaussian noise from seven industries, including oil field, automobile, bearing, electronics, electrolytic aluminum, and iron and steel

TABLE 1. Cohort Studies on Occupational Hearing Loss Caused by Non-Gaussian Noise

| Author | Industry | Type of Work | Year of Follow-up | Subject | | | | Incidence of NIHL (%) | |
				N	Exposure Duration (y)	Use of HPDs	L_{Aeq} [dB(A)]	HFNIHL	SFNIHL
Jing et al. (2012a)	Oil field	Drilling	5	673	(0–30.0)	Not mentioned	(62.8–106.8)	30.6	3.7
Zhao et al. (2014)	Automobile factory	Stamping, welding, general assembly, etc.	5	1102	2.3±1.1	Not mentioned	87.9±7.9	9.3	–
Xia et al. (2004)	Bearing factory	Forging	20	148	20.0	Not mentioned	98.0 (90.0–108.0)	35.8	–
Yu et al. (2017)	Iron and steel plant	—	10	6297	–	Rarely used	(80.6–103.4)	5.1	1.2
Chen & Lin (2010)	Electronics factory	Operator, maintenance worker, and grinding	3	540	–	Not mentioned	88.7±4.4	31.5	3.7
Xu et al. (2014)	Electrolytic aluminum plant	Forging, casting, assembly, molding, etc.	5	1929	8.8±8.7 (1.0–30.0)	Not mentioned	–	11.5	8.1
He et al. (2017)	Automobile factory	Stamping, casting, engine testing, engine assembly, etc.	3	397	(1.0–36.0)	Regularly used	(66.2–101.3)	34.3	2.3
Total	–	–	–	11,086	5.5±6.9 (0–36.0)	–	89.0±7.2 (62.8–108)	10.9	2.9

Rarely used: fewer than 50% of subjects in the included study were reported to use HPDs; Regularly used: not fewer than 50% of subjects in the included study were reported to use HPDs
HFNIHL indicates high-frequency noise-induced hearing loss; HPDs, hearing protection devices; NIHL, noise-induced hearing loss; SFNIHL, speech-frequency noise-induced hearing loss.

TABLE 2. Meta-analysis for Cross-sectional Studies With Non-Gaussian Noise Exposure and its Controls

	Non-Gaussian Noise vs. Non-noise			Non-Gaussian Noise vs. Gaussian Noise		
	WMD/Weighted OR	95% CI	P	WMD/Weighted OR	95% CI	P
Exposure Duration (yrs)	0.93	(−0.23, 2.09)	0.115	−0.18	(−1.03, 0.68)	0.687
Age (yrs)	−0.39	(−3.24, 2.47)	0.790	0.14	(−1.85, 2.13)	0.892
L_{Aeq} [dB(A)]	23.70*	(21.54, 25.86)	0.000	−1.10	(−4.25, 2.05)	0.493
CNE [dB(A)·yr]	–	–	–	−0.84	(−3.64, 1.96)	0.556
Male (%)	2.49	(0.99, 6.24)	0.052	2.39*	(1.29, 4.41)	0.005
Prevalence of HFNIHL (%)	4.46*	(2.80, 7.11)	0.000	2.20*	(1.78, 2.72)	0.000
Prevalence of SFNIHL (%)	6.81*	(3.41, 13.61)	0.000	2.14*	(1.46, 3.13)	0.000

*p < 0.05.
CI indicates confidence interval; HFNIHL, high-frequency noise-induced hearing loss; OR, odds ratio; SFNIHL, speech-frequency noise-induced hearing loss; WMD, weighted mean difference.

plants. The results showed that a total of 11,086 workers from these industries were exposed to 89.0 ± 7.2 dB(A) noise levels. The incidences of HFNIHL and SFNIHL were 10.9 and 2.9%, respectively. In addition, these studies also reported the incidence of hearing loss caused by non-Gaussian noise increased with exposure duration.

Cross-sectional Studies

Cross-sectional Studies on the Prevalence of Occupational NIHL • Nineteen cross-sectional studies on occupational NIHL associated with non-Gaussian noise were included, with a total of 9081 workers exposed to non-Gaussian noise (see Table S1 in Supplemental Digital Content 1, http://links.lww.com/EANDH/A808). The average age and exposure duration were 34.8 ± 8.5 years and 9.6 ± 7.5 years, respectively, and 82.3% were male workers. The average noise level, CNE, and kurtosis for non-Gaussian noise were 88.1 ± 8.5 dB(A), 109.5 ± 20.9 dB(A)·year, and 40.5 ± 80.7, respectively. The prevalence of HFNIHL and SFNIHL among the workers exposed to non-Gaussian noise were 36.1 and 30.0%, respectively.

Cross-sectional Studies Using a Non-noise Exposure Group as a Control • Fifteen cross-sectional studies with nonnoise-exposed population as the control group were included (see Table S2 in Supplemental Digital Content 1, http://links.lww.com/EANDH/A808). There were totally of 8390 subjects, including 5053 non-Gaussian noise-exposed workers and 3337 non-noise exposed subjects (control group). Table 2 shows that there were no significant differences in age, sex, or exposure duration between the non-Gaussian noise-exposed group and the control group (p > 0.05). The average L_{Aeq} in the non-Gaussian noise group was significantly greater than that in the control group (p < 0.05). The prevalence of HFNIHL in the exposed group was 34.5%, which was significantly higher than that (12.9%) in the control group (p < 0.05). The prevalence (8.6%) of SFNIHL in the exposed group was also significantly higher than that (2.4%) in the control group (p < 0.05). The random-effect model of the meta-analysis showed that non-Gaussian noise exposure was a risk factor for HFNIHL with an overall-weighted OR of 4.46 (95% CI: 2.80–7.11). Figure 1 shows the forest plot of meta-analysis for the overall-weighted OR value of HFNIHL between the non-Gaussian noise-exposed group and the non-noise exposure group in each study. Figure 2 shows the forest plot of meta-analysis for the overall-weighted OR value of SFNIHL between the two groups in each study.

Cross-sectional Studies Using a Gaussian Noise Group as a Control • Thirty cross-sectional studies with Gaussian noise-exposed population as a control group were investigated (see

Table S3 in Supplemental Digital Content 1, http://links.lww.com/EANDH/A808). A total of 17,688 subjects were enrolled, including 9127 in the non-Gaussian noise group and 8561 in the Gaussian noise group. The mean kurtosis value (37.1 ± 52.9) of the non-Gaussian noise group was significantly higher than that (3.2 ± 0.3) of the Gaussian noise group (p < 0.05), but there was no significant difference in CNE between the two groups (p > 0.05). The results showed that the prevalence (33.3%) of HFNIHL in the non-Gaussian noise group was significantly higher than that (27.7%) in the control group (p < 0.05). The prevalence (15.9%) of SFNIHL in the non-Gaussian noise-exposed group was also significantly higher than that (13.4%) in the control group (p < 0.05). The random-effect model used in the meta-analysis showed that non-Gaussian noise had a greater impact on HFNIHL than Gaussian noise, with an overall-weighted OR of 2.20 (95% CI: 1.78–2.72). Figure 3 shows the forest plot for overall-weighted ORs of HFNIHL between the non-Gaussian noise group and the Gaussian noise group. Figure 4 shows the forest plot for the overall-weighted OR of SFNIHL between the two groups in each study.

High-frequency Hearing Threshold Levels Associated With Occupational Non-Gaussian Noise Exposure • Table 3 demonstrates the 12 cross-sectional studies on high-frequency hearing threshold levels among workers exposed to non-Gaussian noise in this study. A total of 4475 subjects, mainly from the manufacturing industry, were exposed to 93.2 ± 6.8 dB(A) noise levels. The average high-frequency hearing threshold level at frequencies of 3, 4, and 6 kHz for these workers was 42.1 ± 17.4 dB HL.

Epidemiological Characteristics of Occupational NIHL Associated With Non-Gaussian Noise • Table 4 summarizes the epidemiological characteristics of occupational NIHL associated with non-Gaussian noise based on the cross-sectional studies. A total of 23,261 workers aged 34.9 ± 8.7 years had been exposed to high levels of non-Gaussian noise for 10.7 ± 8.2 years from manufacturing and mining industries. Of these, 83.6% were males. Examples of job duties included forging, riveting, stamping, casting, drilling, molding, finishing, pressing, assembling, welding, grinding, smashing, steel rolling, wood sawing, and machine testing. The mean L_{Aeq}, CNE, and kurtosis for non-Gaussian noise were 88.7 ± 6.9 dB(A), 100.2 ± 14.0 dB(A)·year, and 40.3 ± 79.5, respectively. The prevalence of HFNIHL and SFNIHL associated with non-Gaussian noise were 34.2 and 18.9%, respectively.

The Relationships Between Key Factors and the Prevalence of HFNIHL • Table 5 demonstrates the overall-weighted ORs of the key factors influencing HFNIHL. There were no significant

Study ID	OR (95% CI)	Events, Non-Gaussian noise (n/N)	Events, Non-noise (n'/N')	% Weight
Narlawar, U.W. 2006	2.63 (1.71, 4.06)	82/400	33/370	9.09
Whittaker, J. D. 2014	8.21 (3.01, 22.41)	26/95	5/114	6.77
Liu, J. 2016	1.21 (0.88, 1.66)	111/360	102/378	9.42
Yuan, J.G. 2005	13.59 (6.03, 30.63)	54/88	9/86	7.59
Li, J.F. 2002	1.92 (1.46, 2.53)	511/1456	77/351	9.53
Li, B.W. 2003	4.71 (1.45, 15.30)	71/120	4/17	6.05
Mo, Y.F. 2006	11.51 (7.26, 18.25)	266/410	26/188	8.99
Yang, C.M. 1999	9.70 (4.34, 21.66)	36/63	11/91	7.63
Liu, L.F. 2013	6.43 (3.05, 13.55)	89/404	8/190	7.87
Jing, Q.S. 2012	4.23 (2.91, 6.15)	137/483	42/491	9.27
Lin, L. 2005	5.63 (3.45, 9.18)	99/500	21/500	8.89
Nyarubeli, I.P. 2019	2.10 (1.29, 3.43)	107/221	33/107	8.90
Overall (I-squared = 90.5%, p = 0.000)	4.46 (2.80, 7.11)	1589/4600	371/2883	100.00

NOTE: Weights are from random effects analysis

.0326   1   30.6

n, number of workers suffering from HFNIHL in the non-Gaussian noise group; N, number of workers in the non-Gaussian noise group;
n', number of workers suffering from HFNIHL in the non-noise group; N', number of workers in the non-noise group.
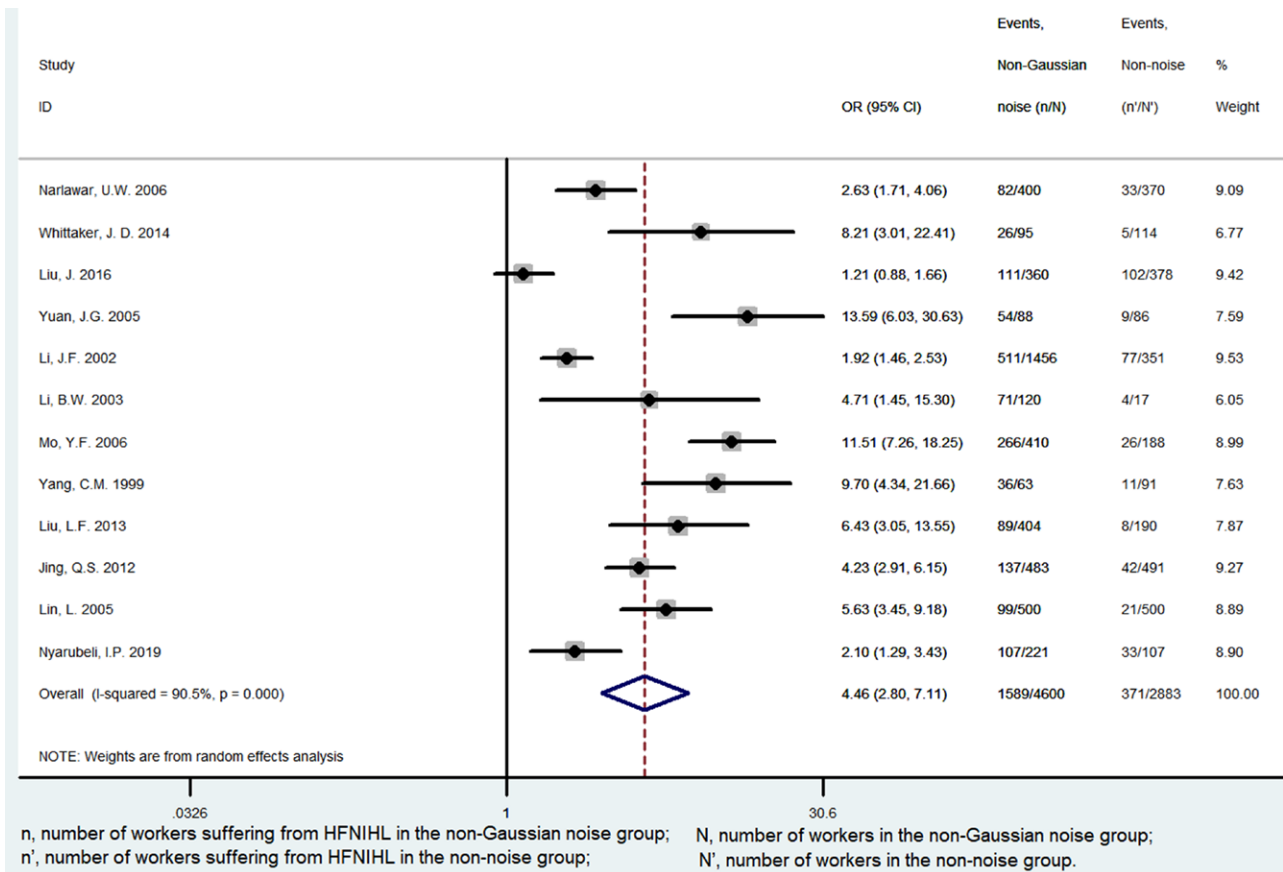
Fig. 1. The forest plot of meta-analysis for the overall-weighted OR value of HFNIHL in the non-Gaussian noise-exposed group with the non-noise exposure group as the control in each study. HFNIHL indicates high-frequency noise-induced hearing loss; OR, odds ratio.

differences between male and female workers (overall-weighted OR = 1.03; 95% CI: 0.56–1.90) ($p > 0.05$). The prevalence of HFNIHL in subgroup $L_{Aeq} > 85$ dB was significantly higher than that in $L_{Aeq} \leq 85$ dB (overall-weighted OR = 3.85, 95% CI: 1.57–9.43). The Chi-square trend test demonstrated that the prevalence of HFNIHL was significantly correlated with age, exposure duration, and CNE. With the age subgroup of 20–30 years as the reference group (OR = 1), the overall-weighted ORs for the subgroups aged 30–40, 40–50, and >50 years were 2.39, 2.89, and 7.07, respectively ($p < 0.05$). As for exposure duration subgroups of <5, 5–10, and ≥10 years, the overall-weighted ORs were 1.00, 1.43, and 1.96, respectively ($p < 0.05$). The prevalence of HFNIHL increased with the increase in exposure duration. The prevalence of NIHL in the 5–10 years' exposure group was 35.0%, which was significantly higher than that (24.1%) in the <5 years' exposure group ($p < 0.05$). The prevalence of HFNIHL in the CNE subgroups of 85–90, 90–95, 95–100, 100–105, and ≥105 dB(A)·year were 23.8, 31.0, 36.3, 41.3, and 60.4%, respectively. With the CNE subgroup of 85–90 dB(A)·year as the reference group (OR = 1), the overall-weighted ORs for the remaining four subgroups were 1.57, 2.65, 5.28, and 7.60, respectively. The trend Chi-square test showed that the ORs increased with CNE levels ($p < 0.05$).

DISCUSSION

The 78 epidemiological studies (with 47,814 study subjects) on occupational NIHL associated with non-Gaussian noise for

this review were conducted in several countries such as China, India, Iran, Nepal, Thailand, Poland, Tanzania, Nigeria, Sweden, the United Kingdom, and the United States. The results showed that non-Gaussian noise was mainly distributed in the manufacturing industry (e.g., automobile, ship, machinery manufacturing, and metal smelting) and the mining industry. In addition, the construction industry might be a source of non-Gaussian noise (Seixas et al. 2012). Thus, non-Gaussian noise is the dominant noise type in manufacturing industries, except that Gaussian noise is predominant in the textile and paper-making industries (Zhou et al. 2020).

In this review, the prevalence of HFNIHL and SFNIHL among manufacturing workers and miners were 34.2 and 18.9%, respectively. Studies on the prevalence of occupational NIHL in each country have been carried out. He et al. (2005) investigated 37 manufacturing industries in China in 2005, and hearing loss was detected in 22.5% of workers. Masterson et al. (2016) analyzed 1,413,789 audiograms of workers from nine US industry sectors in audiometric monitoring programs as part of a hearing conservation program and found 12.94% of participants suffered from hearing impairment at the 0.5, 1, 2, and 4 kHz frequencies in the better-hearing ear. The National Institute of Miners' Health (NIMH) conducted studies on NIHL in various mines in India and found that the prevalence of NIHL among employees was 12.8% (Nandi and Dhatrak 2008).

This review analyzed the effects of individual factors (e.g., age and sex) on occupational NIHL associated with non-Gaussian noise. Workers exposed to non-Gaussian noise were
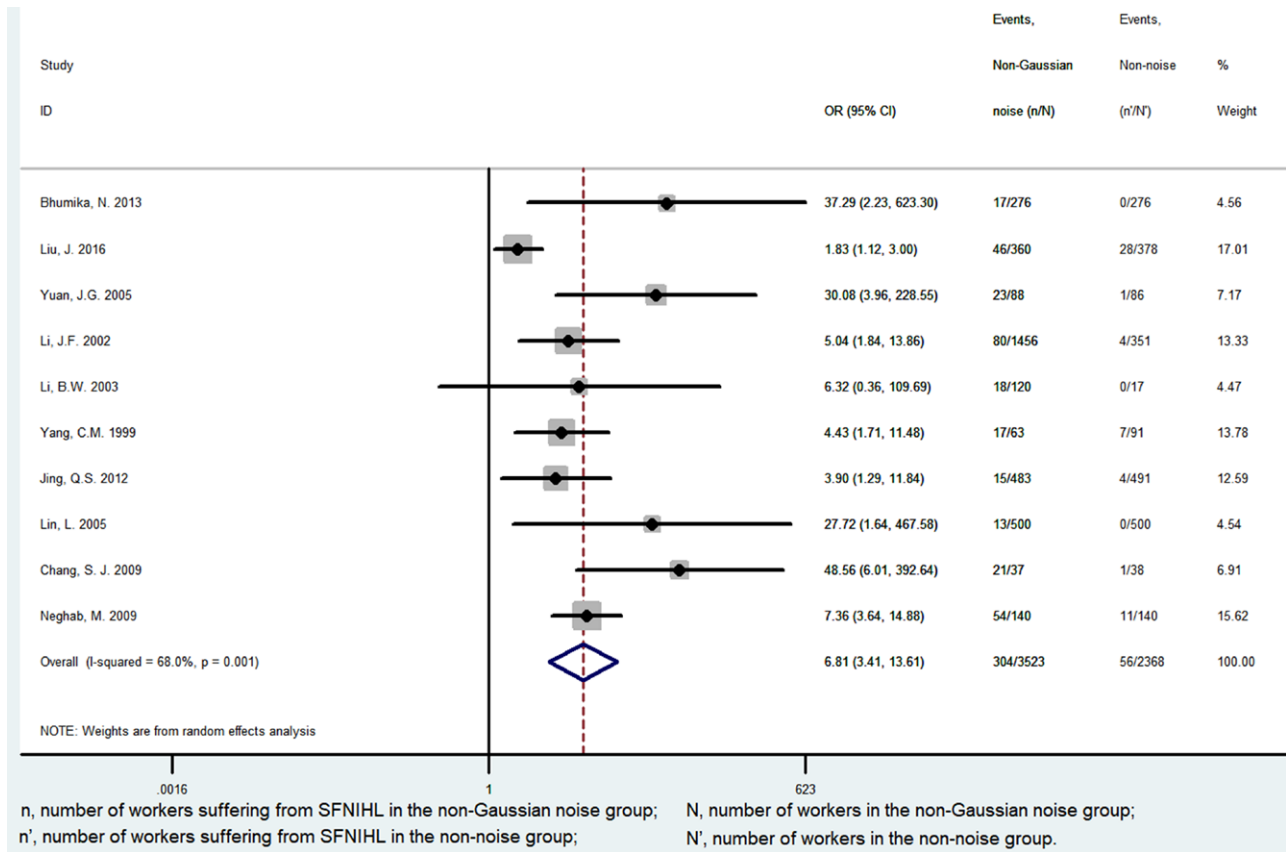
Fig. 2. The forest plot of meta-analysis for the overall-weighted OR value of SFNIHL in the non-Gaussian noise-exposed group with the non-noise exposure group as the control in each study. OR indicates odds ratio; SFNIHL, speech-frequency noise-induced hearing loss.

mainly young adult males. Although male workers had a higher prevalence of HFNIHL than females, there were no significant differences between the male and female workers in this meta-analysis ($p > 0.05$). Some studies (Huang 1994; Zhao et al. 2019) have also reported a significantly higher prevalence in male than female workers, which may be related to the male workers' engagement in heavier job duties with exposure to high levels of noise than female workers. The prevalence of HFNIHL by age group (20–, 30–, 40–, and >50 years) was compared using the Chi-square trend test, and the result showed a much higher prevalence of HFNIHL with increased age, which indicated age as a critical factor influencing workers' HFNIHL. This finding agrees with those of many studies that reported a dose-response relationship between the age of workers and prevalence of NIHL (Maccà et al. 2015; Sriopas et al. 2017; Nyarubeli et al. 2019).

Prevalence of occupational NIHL is also affected by the use of HPDs (e.g., earmuff and earplug). HPD is one of the common methods for preventing occupational NIHL because it can attenuate the noise effects and decrease the risk of hearing loss (Verbeek et al. 2014). Młyński and Kozlowski (2014) also found HPD could be suitable for the protection against impulse noise in metalworking processes. In this review, most included studies reported that workers rarely or never used HPDs, which could be related to the lack of self-protection awareness among workers and the insufficient training on HPD knowledge for workers (Xie et al. 2020). A few studies included in this review reported workers regularly used HPDs, which could be a confounding

factor when interpreting the outcomes of hearing loss in the meta-analysis.

Noise level, one of the most commonly used noise energy indicators, is an essential factor that influences hearing loss. This review showed that the non-Gaussian noise-exposed group with higher L_{Aeq} levels had a greater risk of HFNIHL than the non-noise-exposed group. We also compared the prevalence of HFNIHL between L_{Aeq} subgroups (>85 dB[A] and ≤85 dB[A]) and found a significantly higher prevalence in the >85 dB(A) subgroup. The results indicated that the level of non-Gaussian noise exposure was a harmful factor for workers' hearing and that hearing loss would become more severe with increased noise level. Xie et al. (2011) also found a positive correlation between hearing loss and noise level. Rubak et al. (2006) investigated 788 workers exposed to high levels of noise in 11 industries and observed that noise-exposed workers had an overall two-fold risk of hearing loss than the reference group. Irion (1984) conducted a study involving 1020 persons in a power station with a noise level of more than 85 dB(A) and found that the hearing loss increased as the noise level increased.

A large number of studies reported that workers were exposed to hazardous noise worldwide. Approximately 35 million people are exposed to harmful noise levels in Europe (Sulkowski et al. 2004). Soltanzadeh et al. (2014) reported that the occupational noise level in Iran reached 90.29 dB(A), which significantly exceeded the exposure limit of 85 dB(A). The US CDC estimated that about 9 million workers are exposed to daily average sound levels equal to or greater than 85 dB(A)

Study ID	OR (95% CI)	Events, Non-Gaussian noise (n/N)	Events, Gaussian noise (n'/N')	% Weight
Zhen, J.R. 1996	2.84 (1.44, 5.57)	39/66	27/80	3.10
Zhou, F. 1999	2.26 (1.35, 3.76)	169/689	19/151	3.58
Zhao, Y.M. 2006	1.18 (0.52, 2.67)	22/32	106/163	2.71
Xie, H.W. 2016	0.97 (0.63, 1.48)	86/178	80/163	3.83
You, Q.W. 2006	5.42 (3.47, 8.46)	85/130	76/294	3.77
Zhang, G.Y. 2012	2.59 (1.13, 5.96)	21/38	20/62	2.66
Tao, L.K. 1995	3.62 (2.11, 6.22)	65/120	31/126	3.49
Zhang, Q.N. 2012	1.27 (0.58, 2.78)	66/431	8/64	2.79
Zeng, Y.Q. 2018	0.95 (0.58, 1.54)	138/277	44/86	3.66
Zhang, J. 2010	3.81 (2.23, 6.53)	65/212	21/202	3.50
Zu, A.H. 2012	2.12 (1.37, 3.26)	196/442	35/128	3.81
Ding, G.Y. 1988	5.07 (2.68, 9.60)	63/112	18/89	3.21
Zhen, J.R. 1997	2.94 (2.06, 4.19)	215/271	226/399	4.02
Zhang, L.L. 2006	5.51 (3.35, 9.08)	62/94	78/300	3.62
Lei, S. 2019	1.37 (0.96, 1.94)	231/558	61/179	4.02
Xie, H.W. 2014	2.53 (1.04, 6.14)	60/98	10/26	2.52
Ding, M.P. 1995	1.33 (0.97, 1.83)	345/553	121/218	4.11
Lu, J.Z. 1999	5.58 (2.99, 10.44)	58/132	16/130	3.24
Li, X.C. 2016	4.06 (2.81, 5.87)	313/2285	33/878	3.98
Li, C.Y. 2010	4.43 (2.88, 6.81)	92/168	53/247	3.81
Zhang, H.Y. 2018	2.04 (1.53, 2.73)	192/536	92/429	4.17
Huang, Y. 1998	1.74 (0.39, 7.78)	16/278	2/59	1.39
Tian, K.C. 1996	4.03 (1.74, 9.32)	32/50	15/49	2.65
Chen, L.J. 1998	0.65 (0.21, 1.99)	25/55	9/16	1.99
Lu, C.H. 2014	0.82 (0.40, 1.68)	17/96	20/96	2.97
Cui, S.Z. 1994	2.03 (0.70, 5.90)	33/38	65/85	2.11
Xie, M.Y. 1999	1.48 (0.80, 2.73)	38/329	16/197	3.28
Deng, J.H. 2002	1.11 (0.70, 1.76)	45/130	71/220	3.73
Wu, X.J. 1999	2.11 (1.45, 3.07)	89/135	518/1083	3.96
Lai, J.M. 2007	1.44 (1.17, 1.77)	162/594	483/2342	4.34
Overall (I-squared = 82.0%, p = 0.000)	2.20 (1.78, 2.72)	3040/9127	2374/8561	100.00

NOTE: Weights are from random effects analysis

n, number of workers suffering from HFNIHL in the non-Gaussian noise group; N, number of workers in the non-Gaussian noise group;
n', number of workers suffering from HFNIHL in the Gaussian noise group; N', number of workers in the Gaussian noise group.
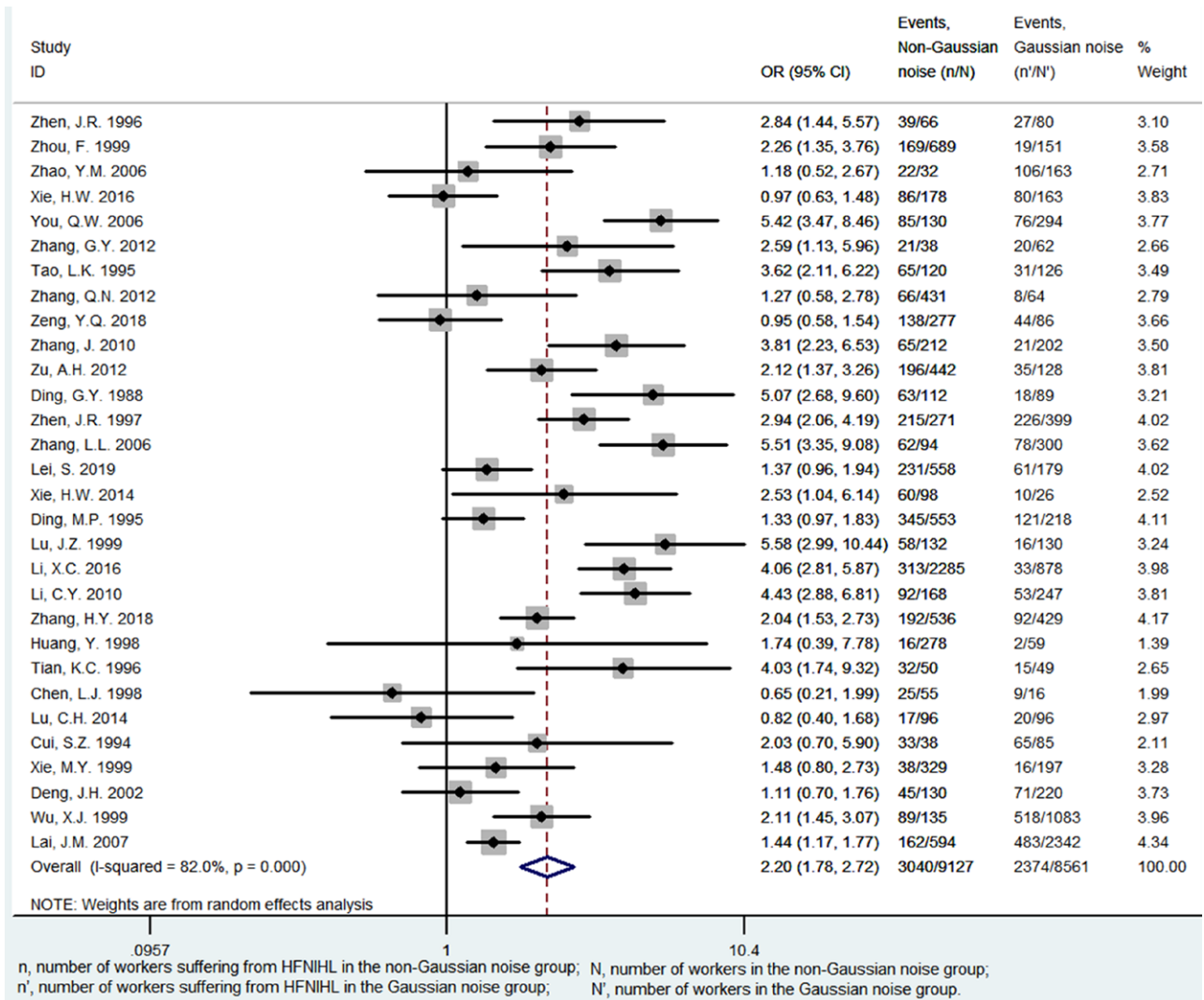
Fig. 3. The forest plot of meta-analysis for the overall-weighted OR value of HFNIHL in the non-Gaussian noise-exposed group with the Gaussian noise-exposed group as the control in each study. HFNIHL indicates high-frequency noise-induced hearing loss; OR, odds ratio.

(Masterson et al. 2015). In this review, a total of 23,261 workers were exposed to the non-Gaussian noise with an average L_{Aeq} of 88.7 ± 6.9 dB(A). Consequently, their average high-frequency hearing threshold level increased to 42.1 ± 17.4 dB HL. It is essential to take measures to lower the noise levels.

Noise exposure duration is another critical factor influencing NIHL. In this review, the average exposure duration in workers exposed to non-Gaussian noise was 10.7 ± 8.2 years. Table 5 demonstrates that the prevalence of NIHL increased with the increase of exposure duration. As for earlier than 10 years of exposure, the prevalence of NIHL after 5–10 years of exposure was significantly higher than less than 5 years of exposure, indicating that NIHL can develop rapidly within 10 years of exposure, especially for non-Gaussian noise exposure. Table 2 and Table 3 in Supplemental Digital Content 1, http://links.lww.com/EANDH/A808 illustrate that non-Gaussian noise is more hazardous than Gaussian noise. Thus, the hearing loss caused by non-Gaussian noise is expected to manifest itself earlier when compared with Gaussian noise exposure.

Cohort studies (Chen and Lin 2010; Jing et al. 2012b; Xu et al. 2014; Zhao et al. 2014; He et al. 2017) also found an increased incidence of HFNIHL with increased noise exposure duration. These results demonstrated that noise exposure duration significantly influences high-frequency hearing loss, and a longer noise exposure duration is associated with a higher prevalence of hearing loss. Pelegrin et al. (2015) conducted a prospective study on NIHL in Spanish workers. Interpreting the logistic regression analysis, workers with pathological audiograms had longer noise exposure duration; thus, they concluded that noise exposure duration is a significant predictor of NIHL. NIHL can result from the cumulative effect of noise exposure. Workers will have increasingly progressive hearing loss if exposed to noise repeatedly, especially when they do not recover from the temporary NIHL. There is also literature indicating that NIHL may progress long after the noise exposure has stopped (Gates et al. 2000). Studies have shown that hearing loss develops most rapidly in the first 10 years of exposure, reaches its peak in 10–15 years, and enters a plateau after 15 years (Bauer et al. 1991; Chen et al. 1992; Li and Shao 2015). This suggests that early hearing protection and intervention for workers exposed to non-Gaussian noise should be carried out during the first 10 years of exposure.
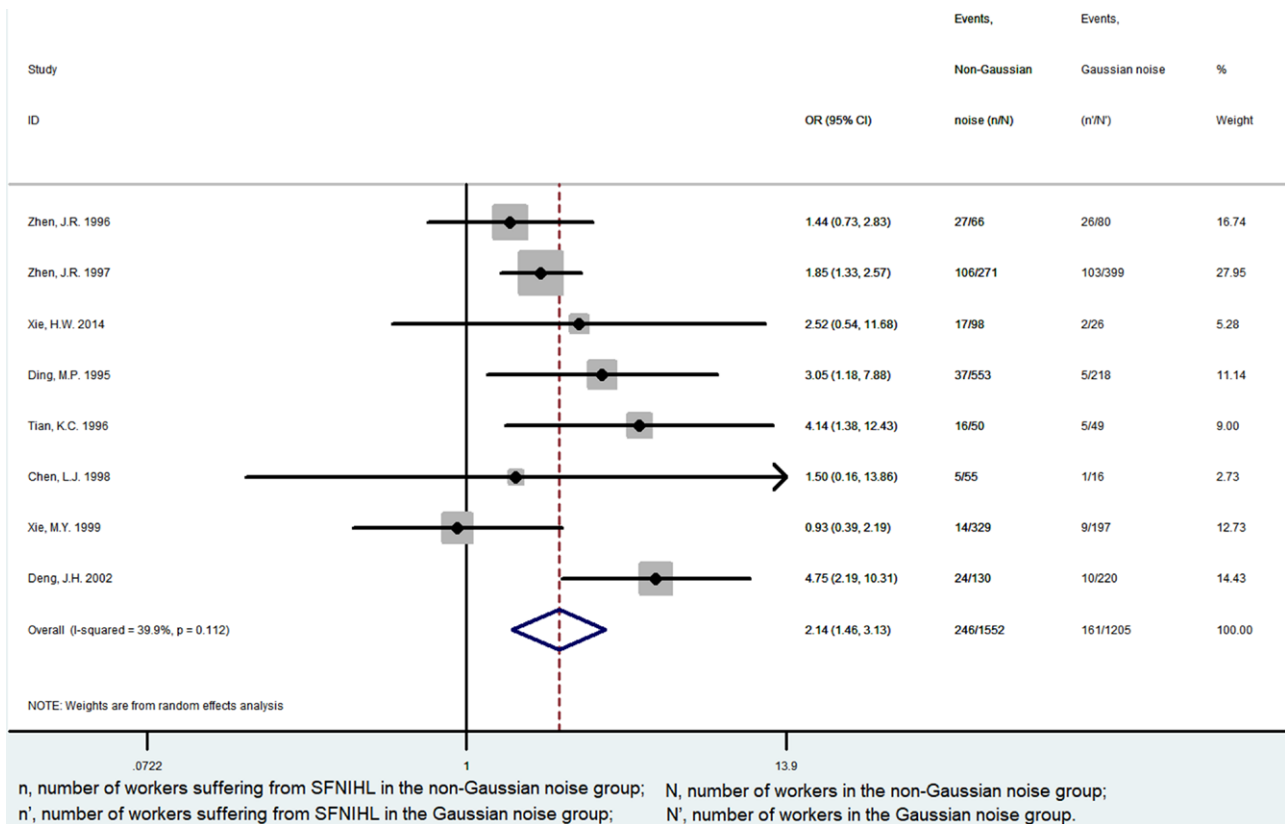
Fig. 4. The forest plot of meta-analysis for the overall-weighted OR value of SFNIHL in the non-Gaussian noise-exposed group with the Gaussian noise-exposed group as the control in each study. OR indicates odds ratio; SFNIHL, speech-frequency noise-induced hearing loss.

CNE can reflect the noise exposure level more comprehensively because it combines both the noise intensity (L_{Aeq}) and exposure duration (Liu et al. 2008). The dose-response relationship is the basis for establishing non-Gaussian noise standards. The trend Chi-square test showed a dose-response relationship between CNE and the prevalence of HFNIHL, and the higher the CNE level, the greater the high-frequency hearing loss. Ding et al. (1995) also found a typical dose-response relationship between CNE of impulsive noise or Gaussian noise and hearing loss among workers at both high and speech frequencies, and the typical dose-response curve was shaped like an "S." These results indicate that CNE is positively correlated with hearing loss and can be applied to measuring and evaluating hearing loss.

Hearing loss is not only related to the noise energy level but is also affected by noise temporal structure. Erdreich (1986) proposed that kurtosis could be used to reflect the impulsiveness and temporal structure of non-Gaussian noise, which provides excellent convenience for classifying non-Gaussian noise and Gaussian noise. It also helped shape the idea that kurtosis could be used as an appropriate metric for quantifying exposure to non-Gaussian noise. In this study, the non-Gaussian noise group had significantly higher kurtosis than the Gaussian noise group, and there was no significant difference in CNE between the two groups ($p > 0.05$). The results showed that the prevalence of HFNIHL in the non-Gaussian noise group was significantly higher than that in the Gaussian noise group (overall-weighted OR=2.20, 95% CI: 1.78–2.72). These findings suggested that non-Gaussian noise could cause more severe hearing loss than Gaussian noise. These results were confirmed by animal experiments. Hamernik et al. (2003) divided 207 chinchillas into 17 groups, and 16 groups were exposed to non-Gaussian noise while the remaining group was exposed to Gaussian noise. All the noises were in the same spectrum and energy level ($L_{Aeq}=100$ dB). It was found that the loss of hair cells in the non-Gaussian noise group was greater than that in the Gaussian noise group. A series of animal experiments were conducted by the Auditory Research Laboratory of the State University of New York at Plattsburgh on hearing loss caused by non-Gaussian noise (Qiu et al. 2006, 2007, and 2013). They found that, under the same L_{Aeq}, non-Gaussian noise caused more significant damage to the cochlear hair cells than Gaussian noise, and the hearing threshold increased faster in the non-Gaussian noise group. Epidemiological studies have reached the same conclusion. Zhang et al. (2012) compared the prevalence of HFNIHL between workers exposed to punching machine noise from a forging workshop and workers exposed to Gaussian noise from a drawbench or an abrasive dust workshop. Although there was no significant difference in CNE between the two groups, the prevalence of HFNIHL was significantly higher among punching workers. Mäntysalo and Vuori (1984) observed that the hearing damage in workers exposed to high levels of impulsive noise in the shipyard is more severe than that of workers exposed to high levels of Gaussian noise in the cable factory. Davis et al. (2012) found that noise with higher kurtosis levels resulted in larger median noise-induced permanent threshold shift at high frequencies than noise with lower kurtosis levels.

Based on the above studies, L_{Aeq} is not able to fully assess the hearing loss induced by non-Gaussian noise. The auditory damage,

TABLE 3. High-frequency Hearing Threshold Levels Among Workers Exposed to Non-Gaussian Noise

Author	Industry	Type of Work	Subject Exposure duration (yr)	Age (yr)	N	L$_{Aeq}$ [dB(A)]	High-frequency Hearing Threshold (dB HL)
Thiery & Meyer-Bisch (1988)	Automobile	Welding, brazing, finishing and assembling	13.8±3.6	34.7±4.7	189	89.5 (87.0–90.0)	24.4±13.7
Kerdonfag et al. (2019)	Steel industry	–	14.0±9.9 (1.0–39.0)	41.7±9.7 (23.0–59.0)	93	(91.8–96.1)	28.1±19.2
Sulkowski & Lipowczan (1982)	Drop-forge factory	Hammer	10.7±7.8	36.3±10.2	424	–	30.4±23.4
Taylor et al. (1984)	Drop forging industry	Hammer	8.7±7.7	34.7±11.2	505	–	55.9±17.7
		Press operators	9.5±7.2	34.3±8.9	211	–	33.0±19.4
Ologe et al. (2006)	Steel rolling mill	Finishing	–	–	13	93	28.3
		Mill floor	–	–	44	86	25.2
		Mechanical workshop	–	–	18	72	25.4
Singh et al. (2013)	Steel Industry	Punching and blanking, forging, molding, grinding, welding and the tool room	8.9±5.5	30.1±7.8	165	96.7	45.0±17.2
Chang & Chang (2009)	A liquefied petroleum gas cylinder infusion factory	Gas-infusion	12.7±7.4	46.7±7.6	37	79.1±5.1	46.3±14.9
Nyarubeli et al. (2019)	Iron and Steel factories	Casting and forging	5.0 (0–24.0)	32.0±8.0	221	92	24.3±9.8
Xie et al. (2015)	Rolling mill and steel structure plant	Rolling steel, finishing, drilling and assembling	9.9±7.4 (1.0–30.0)	37.4±6.5 (21.0–50.0)	98	94.9±4.0	37.5±14.4
Li (2016)	Electronic	Machine tool operating, stamping and inspecting	–	–	2285	(83.1–91.6)	51.1±4.5
Huang & Wu (2004)	Electronics	Wood sawing	4.3 (1.0–10.0)	28.3 (17.0–41.0)	172	–	28.5±11.5
Lei (2019)	Metal processing	–	–	–	558	–	26.8±14.9
Total	–	–	8.9±7.1 (1.0–39.0)	34.0±9.3 (17.0–50.0)	4475	93.2±6.8 (51.5–134.5)	42.1±17.4

including NIHL in occupational populations, may be underestimated using the existing noise measurement and assessment standards (Suvorov et al. 2001; Seixas et al. 2012). Therefore, it is necessary to combine the noise energy metric with the metric reflecting the temporal structure of non-Gaussian noise. Some scholars proposed that the CNE adjusted by kurtosis, also known as "kurtosis-adjusted CNE," could be a suitable metric for assessing the hearing loss induced by non-Gaussian noise. A series of animal experiments found that noise energy and kurtosis are necessary and sufficient for evaluating the hearing loss induced by

TABLE 4. Epidemiological Characteristics of Occupational NIHL Based on Cross-sectional Studies

Type of Study	N	Subject Exposure Duration (yr)	Age (yr)	Male (%)	Noise Energy Level L$_{Aeq}$ [dB(A)]	CNE [dB(A)·yr]	Temporal Structure Kurtosis	Prevalence of NIHL (%) HFNIHL	SFNIHL
Cross-sectional studies with prevalence of NIHL	9081	9.6±7.5 (0.3–41.0)	34.8±8.5 (17.0–63.0)	82.3	88.1±8.5 (68.3–113.0)	109.5±20.9 (82.3–230.0)	40.5±80.7 (3.0–926.0)	36.1	30.0
Cross-sectional studies with a non-noise exposure group as control	5053	15.3±8.9 (0.5–40.0)	37.3±9.1 (17.0–62.0)	86.6	87.7±3.6 (57.0–109.0)	–	–	34.5	8.6
Cross-sectional studies with a Gaussian noise exposure as control	9127	9.0±7.6 (0.5–35.0)	31.9±7.8 (18.0–55.0)	83.5	91.6±4.1 (73.0–118.3)	96.6±7.5	37.1±52.9	33.3	15.9
Total	23,261	10.7±8.2 (0.3–41.0)	34.9±8.7 (17.0–63.0)	83.6	88.7±6.9 (57.0–118.3)	100.2±14.0 (82.3–230.0)	40.3±79.5 (3.0–926.0)	34.2	18.9

CNE indicates cumulative noise exposure; NIHL, noise-induced hearing loss; HFNIHL, high-frequency noise-induced hearing loss; SFNIHL, speech-frequency noise-induced hearing loss.

TABLE 5. Key Factors Influencing HFNIHL

Factors	Groups	HFNIHL%	Overall-weighted OR	95% CI	Chi-square Trend Test
Sex	Male	33.4	1.03	0.56–1.90	–
	Female	23.2			
Age (yrs)	>50	91.7	7.07	0.77–64.58	$Z = 5.37$, $p < 0.001$
	40–	81.8	2.89	0.74–11.38	
	30–	43.3	2.39	1.20–4.76	
	20–	27.8	1.00	–	
Exposure duration (yrs)	≥10	47.7	1.96	1.59–2.43	$Z = 15.09$, $p < 0.001$
	5–	35.0	1.43	1.22–1.68	
	<5	24.1	1.00	–	
L_{Aeq} [dB(A)]	>85	47.8	3.85	1.57–9.43	–
	≤85	27.4			
CNE [dB(A)·yr]	≥105	60.4	7.60	3.24–17.80	$Z = 11.47$, $p < 0.001$
	100–	41.3	5.28	2.08–13.45	
	95–	36.3	2.65	1.66–4.25	
	90–	31.0	1.57	1.05–2.36	
	85–	23.8	1.00	–	

95% CI indicates 95% confidence interval; CNE, cumulative noise exposure; HFNIHL, high-frequency noise-induced hearing loss; OR, odds ratio.

non-Gaussian noise. Moreover, under the same L_{Aeq} condition, as the kurtosis value of noise increased, the hearing loss also increased until it tended toward saturation (Qiu et al. 2006, 2013). Some investigations were also performed on kurtosis-adjusted CNE (Xie et al. 2016). Data were collected from 163 workers exposed to Gaussian noise and 178 workers exposed to non-Gaussian noise in Henan and Zhejiang provinces of China. The results showed that, in the same CNE range, the prevalence of high-frequency hearing loss associated with non-Gaussian noise was always higher than that of Gaussian noise when CNE was not adjusted by kurtosis. After CNE was adjusted by kurtosis, the difference in high-frequency hearing loss between the two groups almost disappeared, and the dose-response curves of the two groups nearly overlapped. The results indicated that kurtosis-adjusted CNE could well reflect the hearing loss induced by non-Gaussian noise and was expected to be a specific metric for assessing the risk of hearing loss associated with non-Gaussian noise.

This review had several limitations: (a) Because there are few cohort studies on non-Gaussian noise, only seven cohort studies have been included, which limited the determination of the causal relationships between non-Gaussian noise exposure and hearing loss; (b) There are few epidemiological studies on kurtosis under non-Gaussian noise exposure, which leads to insufficient sample size of kurtosis in statistical analysis; (c) There is no literature to analyze the relationship between the non-Gaussian noise exposure characteristics and SFNIHL, which is also a deficiency; (d) This review adopted the Chinese definition of HFNIHL (an average hearing threshold of ≥40 dB HL at frequencies of 3, 4, and 6 kHz) as one of the inclusion criteria, which would lead to the omission of the occupational population with mild HFNIHL.

CONCLUSIONS

Based on the findings discussed above, this review can draw the following conclusions: (1) Most of the people exposed to non-Gaussian noise were young male workers mainly engaged in the manufacturing and mining industries, and the average exposure duration was nearly 10 years. (2) Workers exposed to non-Gaussian noise suffered from more significant hearing loss than those exposed to Gaussian noise or not exposed to noise.

(3) Age, exposure duration, noise level, and noise temporal structure were the main factors affecting occupational NIHL. (4) The L_{Aeq} alone is not sufficient to quantify non-Gaussian noise exposure, and a combination of kurtosis and noise energy metrics (e.g., L_{Aeq}) should be used. Further efforts are needed to reduce non-Gaussian noise exposure and protect the hearing health of exposed workers. It is necessary to carry out a large number of cross-sectional studies using kurtosis-adjusted CNE or kurtosis-adjusted L_{Aeq} for re-establishing the dose-response relationship between new metrics of noise exposure and NIHL. Prospective studies on non-Gaussian noise are also important.

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