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Evaluating the Risk of Noise-Induced Hearing Loss Using Different Noise Measurement Criteria

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Abstract

Objectives: This article examines whether the Occupational Safety and Health Administration's (OSHA) average noise level (L_{AVG}) or the National Institute of Occupational Safety and Health's (NIOSH) equivalent continuous average (L_{EQ}) noise measurement criteria better predict hearing loss.
Methods: A cohort of construction workers was followed for 10 years (2000–2010), during which time their noise exposures and hearing threshold levels (HTLs) were repeatedly assessed. Linear mixed models were constructed with HTLs as the outcome, either the OSHA (L_{AVG}) or NIOSH (L_{EQ}) measurement criteria as the measure of exposure, and controlling for age, gender, duration of participation, and baseline HTLs (as both a covariate or an additional repeated measure). Model fit was compared between models for HTLs at 0.5, 1, 2, 3, 4, 6, and 8 kHz using the Akaike information criterion (AIC). The 10th, 50th, and 90th percentiles of hearing outcomes predicted by these models were then compared with the hearing outcomes predicted using the ISO 1999:2013 model.
Results: The mixed models using the L_{EQ} were found to have smaller AIC values than the corresponding L_{AVG} models. However, only the 0.5, 3, and 4 kHz models were found to have an AIC difference greater than 2. When comparing the distribution of predicted hearing outcomes between the mixed models and their corresponding ISO outcomes, it was found that L_{EQ} generally produced the smallest difference in predicted hearing outcomes.
Conclusions: Despite the small difference and high correlation between the L_{EQ} and L_{AVG}, the L_{EQ} was consistently found to better predict hearing levels in this cohort and, based on this finding, is recommended for the assessment of noise exposure in populations with similar exposure characteristics.

Keywords: exposure assessment; hearing; noise

Background

It is estimated that about 24 million workers are exposed to hazardous levels of occupational noise each year in the USA alone (Tak *et al.*, 2009). Prolonged exposure to hazardous noise can lead to noise-induced hearing loss (NIHL), which is estimated to affect 11.4% of the working population in the USA (Tak and Calvert, 2008). NIHL can diminish a worker's ability to detect audible warnings and hinder communication with coworkers (Morata *et al.*, 2005) and may also increase the risk of injury in the workplace (Moll van Charante and Mulder, 1990; Barreto *et al.*, 1997; Choi *et al.*, 2005; Picard *et al.*, 2008; Cantley *et al.*, 2015a, 2015b). Outside of the workplace, those with NIHL can feel socially isolated and have a higher prevalence of depression and anxiety compared to those without hearing loss (Melamed *et al.*, 1992).

Regulations and recommendations with regards to occupational noise exposure have changed since the first noise exposure limit was introduced in the 1950s (McIlwain *et al.*, 2008). Before the founding of the Occupational Safety and Health Administration (OSHA), the Department of Labor (DOL) used its authority under the Walsh–Healey Public Contracts Act to propose a permissible exposure limit (PEL) for noise of 85 dBA with a time–intensity exchange rate (ER)—i.e. the amount of change in average noise level (L_{AVG}) needed to double or halve the allowable exposure time—varying between 2 and 7 dB based on the intermittency of the noise exposure (Department of Labor, 1968). However, following input during the public rulemaking process, this standard was replaced by a PEL of 90 dBA with a simplified 5 dB ER, which was adopted by OSHA when that agency was established in 1971 and which remains in effect today (Department of Labor, 1971, 1981, 2004; Suter, 1992). In 1972, the National Institute of Occupational Safety and Health (NIOSH) released its initial 'Criteria for a recommended standard for occupational exposure to noise' in which NIOSH 'reluctantly concurred with the generally acceptable 90 dBA exposure level for an 8-hour day'. However, NIOSH also recognized the need to reducing the 8-h exposure level to 85 dBA based on the evidence presented in the document (NIOSH, 1972). In this document, NIOSH did not take a position on the appropriate ER. In 1994, the American Conference of Governmental Industrial Hygienists (ACGIH) revised its threshold limit value for noise to be 85 dBA with a 3 dB ER (Sliney, 1993). NIOSH revisited the issue in 1998 when they released a revised 'Criterion for a recommended standard occupational exposure to noise' with a recommended exposure limit of 85 dBA and a 3 dB ER (NIOSH, 1998). The difference between the 5 dB and 3 dB ERs has a major impact on the allowable exposure durations for high levels of intermittent noise. For example, if the occupational exposure limit (OEL) for noise is 85 dBA as an 8-h time-weighted average with a 5 dB ER would allow for that worker to be exposed to 100 dBA of noise for 1 h, whereas the 3 dB ER would allow that worker to be exposed to 94 dBA for 1 h. A difference of 3 dB over 8 h is approximately a doubling of sound power (Earshen, 2000). For truly non-varying noise, the ER used makes no difference when comparing the measurements to the same OEL, as there is no variability in levels and hence no role for the time–intensity trading relationship summarized by the ER. However, as noise becomes more variable, as is commonly the case in many industries such as construction, the difference between the two ERs becomes increasingly important (Petrick *et al.*, 1996; Neitzel *et al.*, 1999).

The current debate around the 5 and 3 dB ER

The divergence between the OSHA regulation and NIOSH recommendation for occupational noise exposure has been a point of contention in the industrial hygiene profession (Dobie and Clark, 2013, 2015; Morata *et al.*, 2015; Suter, 2015). However, much of the debate has focused on the differing ERs rather than the differing exposure limits. The 3 dB ER is based on the equal energy hypothesis, which states that an equal amount of sound energy will produce an equal amount of hearing damage regardless of the temporal distribution of the exposure over a work shift or longer period (Suter, 1992). This was supported mainly by the research done by Eldred *et al.* in 1955 and was further buttressed by Burns and Robinson in 1970 (Suter, 1992). Since then several studies have provided further support to the equal energy hypothesis, and field studies using the 3 dB ER have found NIHL rates that are similar to those documented in ISO 1990:1999 (now ISO 1999:2013) (Passchier-Vermeer, 1969; EPA, 1973, 1974; Johansson *et al.*, 1973; ISO, 2013).

Unlike the 3 dB ER, the 5 dB ER used by OSHA attempts to account for predictable, intermittent exposure to noise (e.g. noise exposures interrupted by regularly spaced quiet breaks) that may occur in the workplace. However, there is no formal definition in OSHA's noise standard of what the distinction is between continuous and intermittent noise. The 5 dB ER was first suggested in a set of damage risk criteria curves published by the Committee on Hearing, Bioacoustics, and Biomechanics' (CHABA) Intersociety Committee in its 1967 guidelines for controlling noise exposure

(Van Atta *et al.*, 1967). ACGIH also initially endorsed a 5 dB ER in 1969 (Suter, 1988). In the same year, the DOL adopted a regulation virtually identical to ACGIH's standard (Suter, 1988).

Despite the fact that most countries have adopted the 3 dB ER for regulatory standards and that much of the published literature supports using the 3 dB ER, some authors argue that there is insufficient evidence to support this presumably more protective ER (Clark, 1991; Ward, 1991; Suter, 2003; Dobie and Clark, 2013). The main argument put forth by those opposed to the 3 dB ER is that there are very few modern studies examining whether the 3 or 5 dB ER produces better exposure estimates for predicting NIHL, and some older studies found that using a 3 dB ER would lead to an overestimated risk of NIHL (Johansson *et al.*, 1973).

Because it is widely accepted that hazardous noise exposure leads to NIHL, it is unethical to conduct experimental human exposure studies. Animal studies, primarily of chinchillas (Martin, 2012), have found that the same amount of noise exposure produces a similar amount of NIHL regardless if the noise exposure occurs with breaks or continuously, suggesting that the equal energy hypothesis, and thus the 3 dB ER, is acceptable (Hamernik *et al.*, 2007; Qiu *et al.*, 2007). However, there is still considerable uncertainty when extrapolating these results to humans because of inter-species differences in NIHL risk and the use of noise exposures that are not characteristic of exposures in the workplace (Clark *et al.*, 1987; Fredelius and Wersäll, 1992; Pourbakht and Yamasoba, 2003). Studies of highly exposed worker populations are challenging because of the need for long-term access to, and cooperation from, the workers. In addition, OSHA's hearing conservation amendment in 1981 required employers to provide an effective hearing conservation program to all employees exposed >85 dBA as an 8-h time-weighted average (TWA) (Department of Labor, 1981). This resulted in a large increase in the use of hearing protection devices (Suter, 2009), which substantially complicates the estimation of personal noise exposures and subsequent study of NIHL risk.

Annual audiometric evaluations are used to determine the degree of change in hearing over time, which may be the result of noise exposure during the interval between tests. According to both the OSHA noise standard and recommended practice, workers should receive a baseline audiogram before employment or being assigned to an area with hazardous noise. The test measures pure-tone hearing threshold levels (HTLs) at various audiometric test frequencies (0.5, 1, 2, 3, 4, 6, and sometimes 8 kHz) after a quiet period of at least 14 h (OSHA, 2010). The worker is then given a subsequent audiogram annually. Evaluation of within-worker changes in hearing thresholds between baseline and subsequent audiograms allows for surveillance and identification of NIHL. While large, longitudinal audiometric datasets are maintained by corporations and organizations in the USA and globally, these datasets are often not available to researchers, and the quality of the audiometric measurements (and supporting noise measurement data) contained in the datasets can be highly variable because of variations in testing procedures and environments, as well as supporting information collected at the time of the test (Rabinowitz *et al.*, 2012; Mosites *et al.*, 2016).

To overcome these difficulties, we have re-analyzed exposure and audiometric data from a research cohort of construction apprentices that were first described in Seixas *et al.* (2004), and subsequently in 2012 (Seixas *et al.*, 2012). This inception cohort was chosen because of reported infrequent use of hearing protection and the availability of high-quality baseline and annual audiometric test data accompanied by a robust set of longitudinal noise measurements (Neitzel *et al.*, 2011; Seixas *et al.*, 2012). Using linear mixed models, we estimated the amount of NIHL experienced by these workers at the 0.5, 1, 2, 3, 4, 6, and 8 kHz hearing frequencies when using the 3 dB ER as well as the 5 dB ER to estimate noise exposure. We then compared the models to see which best fit the observed changes in audiometric hearing thresholds. Predictions from both models were then compared to the International Organization for Standardization (ISO) model ISO 1999:2013 (ISO, 2013) for estimating NIHL.

Methods

The exposure and audiometric data for this analysis come from a 10-year longitudinal study of commercial construction apprentices from eight different trades described previously by Seixas et al. (2005b, 2012). The study was divided into two different phases. In Phase 1 (2000–2005), construction apprentices were recruited during their first year of apprenticeship training and were given baseline questionnaires and audiometric tests at 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz using a Tremetrics RA 300 audiometer with TDH-39 headphones in a test van meeting OSHA's requirements for background noise (Seixas *et al.*, 2005b). Subjects were then given follow-up tests approximately every year for 4 years. Graduate students assumed to have non-harmful (i.e. <70 dBA) occupational exposures were recruited as control subjects (EPA, 1974). Subjects who had completed at least two tests were re-recruited for additional yearly audiometric tests for another 4 years during Phase 2 (2006–2010) (Seixas *et al.*, 2012). Audiograms were obtained at 0.5, 1, 2, 3, 4, 6, and 8 kHz using a Grason–Stadler GSI-61 audiometer with ER-3A insert earphones (Eden Prairie, MN) in a test booth meeting the American National Standard Institute's (ANSI) criteria for an audiometric test environment (Seixas *et al.*, 2012). To account for the two different phases, a dummy variable was included in all statistical models to control for the phase of the study.

Exposure to noise was assessed using a task-based approach as described by Neitzel *et al.* (2011). The task-based noise levels were calculated from 1310 full-shift noise measurements (with noise levels data logged at 1-min intervals and simultaneous recording of task involvement and timing by subjects) collected between 1997 and 2008 on commercial construction sites (Seixas *et al.*, 2012). Information on task duration from the questionnaires was combined with task-specific noise levels and normalized to a 2000-h working year to account for the large variability in the number of hours worked across subjects (Seixas *et al.*, 2012). Exposure metrics were calculated for each subject within the interval between audiometric tests and also cumulated over the subject's full duration in the study. Equation 1 from Seixas *et al.* (2012) calculates the interval-specific L_{EQ}—the equivalent continuous sound level using a 3 dB ER and no threshold—where L_t is the mean L_{AVG} level for task t, which was done for H hours as reported by individual i in the subject-interval j lasting Y years, and L_{NC} denotes non-construction hours in noisy jobs that were assigned a level of 85 dBA.

$$L_{EQijTB2000} = 10\log10\Big[\frac{1}{2000 \times Y_{ij}} \Big(\big(\sum_{t=1}^{T} H_{ijt} 10^{L_t/10}\big) + \big(H_{NCij} \times 10^{L_{NC}/10}\big)\Big)\Big]. \quad (1)$$

We used Equation 2 to calculate the interval-specific task-based L_{AVG}, which is the average sound level using a 5 dB ER and an 80 dBA threshold, normalized to a 2000-h working year.

$$L_{AVGijTB2000} = 16.61\log10\Big[\frac{1}{2000 \times Y_{ij}} \Big(\big(\sum_{t=1}^{T} H_{ijt} 10^{L_t/16.61}\big) + \big(H_{NCij} \times 10^{L_{NC}/16.61}\big)\Big)\Big]. \quad (2)$$

Cumulative exposure was calculated for each individual total number of years between their first and last audiometric tests. The resulting cumulative exposure estimates are presented in units of dB-years (e.g. the product of an exposure intensity and duration).

Controls were assigned an exposure of 70 dBA because noise exposure at this level will not cause any measurable hearing loss (EPA, 1974). Pearson's correlation was calculated to measure the correlation between the L_{EQ} and L_{AVG} for each subject over each study interval and cumulatively for the study duration. The ratio of the L_{MAX} to L_{EQ} was calculated, using logarithmic averaging to account for the fact that decibels are log-scale measurements, to determine the 'peakiness' of the exposure. We previously developed and applied this ratio to assess the presence of intense exposures to noise throughout the day from personal dosimetry data using information from two available and robust exposure metrics. An alternative metric for peak exposure, the peak level (L_{Peak}), is known to be susceptible to artifacts from contact with clothing or other objects (Neitzel *et al.*, 1999, 2009; Seixas *et al.*, 2005a). An indicator variable was used to identify exposures with high peakiness (L_{MAX}/L_{EQ} ratio >50).

Linear mixed models were developed to predict HTLs in each ear over time at 0.5, 1, 2, 3, 4, 6, and 8 kHz; these are the audiometric test frequencies recommended as part of a comprehensive hearing loss prevention program (NIOSH, 1998). Additionally, linear mixed models were developed to predict the average HTLs at the 2, 3, and 4 kHz frequency, which is used by OSHA to determine whether a standard threshold shift (STS) has occurred (OSHA, 2010). Noise exposure metrics were transformed by subtracting 70, thus giving an 'unexposed' level of 0 dBA. Models were run using either the L_{AVG} or L_{EQ} exposure metric. The models were run using the combined data from Phases 1 and 2 so that our results could be compared to those of Seixas *et al.* (2012). The models were adjusted for the baseline covariates, age (<30 years or ≥30 years, based on the distribution of ages in the cohort) and gender. The models included random intercepts for subjects (b_{0i}), dominant ears nested within subjects ($b_{oi\bullet l}$), and a random slope for years since baseline at the subject level ($b_{1i\bullet l}$). An additional set of models was developed using the exposure metrics described previously, but which included the baseline hearing thresholds as an additional covariate. This was done to compare the model results to what was found by Seixas *et al.* (2012).

The general equations for the linear mixed models are presented in Equation 3 where i indexes the subject $i_1,\ldots,i_{316}$, l the ear (dominant or non-dominant hand side) $l_1,\ldots,l_{617}$, and t indexes visit time since baseline $t_1,\ldots,t_9$ (Seixas *et al.*, 2012). The term T_{it} indexes the number of years for a subject since baseline at time t, X_{it} is the subject's cumulative noise exposure at time t, and $Z_{it\cdot l}$ represents the other fixed effect covariates for ear l nested within subject i at time t. By including the number of years since baseline and the cumulative noise exposure, it was possible for the model to account for the effect of ageing in addition to noise exposure on HTLs.

$$Y_{it\cdot l} = \beta_0 + (b_{0i} + b_{0i\cdot l}) + (\beta_1 + b_{1i\cdot l})T_{it} + \beta_2 X_{it} + \beta_3 T_{it} + \gamma Z_{it\cdot l} + \varepsilon_{it\cdot l}. \quad (3)$$

All models were run in STATA 14 (College Station, TX) using restricted maximum likelihood estimates and an unstructured covariance. This was done to minimize the bias in the variance component while providing the best model fit and to be consistent with the previous analysis by Seixas *et al.* (Corbeil and Searle, 1976; Littell *et al.*, 2000; Seixas *et al.*, 2012). The fit of the four L_{EQ} and L_{AVG} models (L_{EQ} controlling for baseline versus baseline as an additional repeated measure and L_{AVG} controlling for baseline versus baseline as an additional repeated measure) was compared by using the Akaike information criterion (AIC), a goodness of fit statistic that penalizes complex models (Akaike, 1974). Models with lower AIC values were deemed to better fit the data. The difference in AIC scores between the L_{EQ} and L_{AVG} models was calculated. A difference of 0–2 indicates that there is substantial evidence that both models fit the data, a difference of 4–7 indicates that one model fits the data considerably better, and a difference >10 indicates that one model does not fit the data (Burnham and Anderson, 2002).

The 10th, 50th, and 90th percentiles of hearing outcomes from the four models were compared with the 10th, 50th, and 90th percentiles estimated levels of hearing loss associated with age and noise (HTLAN) predicted using the L_{EQ} and L_{AVG} exposure metrics in the model proposed in ISO 1999:2013 (ISO, 2013). Briefly, this was done by first calculating the median level of predicted noise-induced permanent threshold shift (NIPTS) at the 0.5, 1, 2, 3, 4, and 6 kHz hearing frequency for each worker using Equation 4 (from ISO 1999:2013) (ISO, 2013) for both the L_{EQ} and L_{AVG} where N_{50} is the predicted median NIPTS, μ and υ represent frequency-dependent correction factors (see Supplementary Table S1, available at the *Annals of Work Exposures and Health* online), t represents the length of exposure, t_0 represents 1 year, $L_{EX,8h}$ represents noise exposure for an 8-h working day (either L_{EQ} or L_{AVG}), and L_0 represents the frequency-dependent sound level at which effect on hearing is negligible (ISO, 2013). For participants who had an exposure duration less than 10 years, N was extrapolated using Equation 5 where $N_{50,\,t<10}$ represents the median NIPTS for exposures less than 10 years, t represents the exposure time (in years), and $N_{50,\,t=10}$ represents the estimated NIPTS at 10 years of exposure. Assuming a Gaussian (normal) distribution, the ISO model provides multiplier values that can be used with adjustment factors to calculate the 10th and 90th percentiles of the NIPTS distribution.

$$N_{50} = \left[\mu + \upsilon \times log\left(t/t_0 \right)\right] \times (L_{EX,8h} - L_0)^2, \quad (4)$$

$$N_{50,t<10} = \frac{log(t+1)}{log(11)} \times N_{50,t=10}. \quad (5)$$

HTLs as a function of age are discussed in detail and can be obtained from ISO 7029:2017 (ISO, 2017). HTLs as a function of age were calculated for the same audiometric frequencies as NIPTS using Equation 6 (from ISO 1999:2013), where $H_{md,\,y}$ is the median hearing threshold due to age, a is the gender and frequency adjustment factor, y is the person's age, and $H_{md;18}$ is the median hearing threshold of an ontologically normal person, that is 18 years old. Because the equation centers the age at 18, the $H_{md;18}$ term is taken as 0. Different percentiles can be calculated for each frequency using the provided multiplier and adjustment factors. The HTL associated with age and noise was calculated at the 10th, 50th, and 90th percentiles using Equation 7 where H' is the hearing threshold associated with age and noise exposure, H is the hearing threshold associated with age, and N is the permanent threshold shift caused by noise exposure for the respective frequency and percentile.

$$H_{md,y} = a(y-18)^2 + H_{md;18}, \quad (6)$$

$$H' = H + N - \frac{H \times N}{120}. \quad (7)$$

Results

Figure 1 presents scatter plots of the L_{EQ} and L_{AVG} for each worker at each interval (Fig. 1a) at which their noise exposure was estimated, as well as for their cumulative exposures (Fig. 1b). The L_{EQ} measurements were on average 3–4 dB higher than their associated L_{AVG} measurements. For both interval-specific and cumulative exposures, the L_{EQ} and L_{AVG} measurements were highly and significantly correlated (r = 0.968 and r = 0.974, respectively). The number of subjects available at each follow-up is displayed in Table 1.

Table 2 compares the AIC values for both the L_{EQ} and L_{AVG} models with and without the baseline HTL covariate at the 0.5, 1, 2, 3, 4, 6, and 8 kHz audiometric test

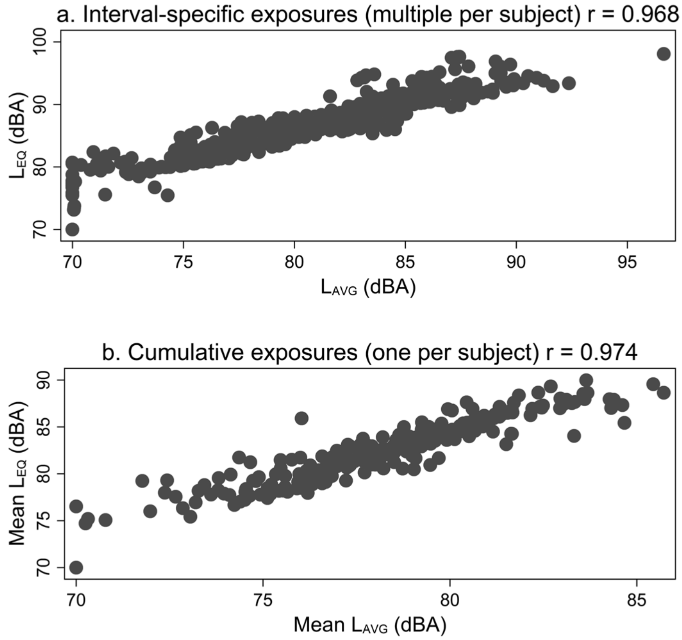

Figure 1. (A) Interval-specific exposures' scatter plot and correlation of L_{EQ} and L_{AVG} exposures. (B) Cumulative exposures' scatter plot and correlation of L_{EQ} and L_{AVG} exposures.

Table 1. The number of subjects at each follow-up.

Time point	Number of subjects
1	316
2	308
3	308
4	259
5	203
6	132
7	110
8	86
9	41

frequencies. When the baseline HTLs were included, the L_{EQ} models fit the data better than L_{AVG} models at each test frequency. However, only the 0.5, 3, and 4 kHz test frequencies were found to have an AIC difference >2, and only the 4-kHz frequency had a difference >4. When the baseline HTLs were not included as a covariate and instead treated as additional repeated measurements, the L_{EQ} models better fit the data at all the test frequencies except for 2 kHz. In addition, the difference between the L_{EQ} and L_{AVG} models' AIC decreased at all the test frequencies except for the 3 and 4 kHz frequencies, where the differences increased by about 1–2. The AIC for the mixed model using the L_{EQ} for the average of the 2, 3, and 4 kHz outcome was found to be 7.42 points lower than the L_{AVG} model (i.e. 19171.54–19178.96) suggesting that the L_{EQ} model better fits the audiometric data at the frequencies used by OSHA to determine whether a STS has occurred.

The fixed and random effects from the L_{EQ} and L_{AVG} models with the baseline HTLs for the 4-kHz test frequency are presented in Supplementary Table S3, available at the *Annals of Work Exposures and Health* online. The coefficients associated with each covariate were generally similar between the L_{EQ} and L_{AVG} 4-kHz models. Those workers with higher baseline hearing levels were found to suffer worse hearing loss because of noise during the study than those in the baseline group in both models. Cumulative noise exposure had a small, but significant effect on hearing levels. This trend was consistent at these three frequencies that had an AIC difference >2, except at the 0.5 kHz frequency where cumulative exposure was found to be a significant predictor of hearing loss in the L_{EQ} model, but not in the L_{AVG} model.

Table 3 presents the fixed and random effects for the L_{EQ} and L_{AVG} models with the additional repeated measurements. The coefficients for each covariate were very similar except for the number of years since baseline, which was found to not be associated with changes in the HTLs in the L_{EQ} nor the L_{AVG} models.

The comparison between the 10th, 50th, and 90th percentiles of hearing loss at the 0.5, 1, 2, 3, 4, and

Table 2. Comparison of AIC values for the L_{EQ} and L_{AVG} models at 0.5, 1, 2, 3, 4, 6, and 8 kHz audiometric frequencies.

Audiometric frequency (kHz)	Models with baseline HTLs			Models without baseline HTLs		
	L_{EQ}	L_{AVG}	Difference (L_{EQ}–L_{AVG})	L_{EQ}	L_{AVG}	Difference (L_{EQ}–L_{AVG})
0.5	16,858.24	16,860.76	−2.52	20,010.75	20,013.18	−2.43
1	16,410.74	16,412.56	−1.82	19,459.59	19,461.00	−1.41
2	17,098.14	17,098.55	−0.41	20,226.13	20,226.05	0.08
3	17,468.53	17,471.47	−2.94	20,872.27	20,877.10	−4.83
4	18,538.37	18,542.41	−4.04	22,383.88	22,389.32	−5.44
6	19,394.87	19,395.82	−0.95	23,475.21	23,475.85	−0.64
8	19,928.21	19,928.87	−0.66	23,756.35	23,756.39	−0.04

Table 3. Fixed and random effects for the L_{EQ} and L_{AVG} models without baseline HTLs covariate for the 4-kHz hearing frequency.

Fixed effects	4 kHz L_{EQ}			4 kHz L_{AVG}		
	Coefficient	SE	*P* value	Coefficient	SE	*P* value
Intercept	3.21	1.70	0.06	3.23	1.70	0.058
Phase 2	2.42	0.51	<0.001	2.49	0.51	<0.001
Age (>30)	7.55	1.57	<0.001	7.50	1.57	<0.001
Gender (male)	7.41	1.82	<0.001	7.39	1.82	<0.001
Years since baseline	−0.06	0.14	0.680	0.11	0.12	0.367
Noise exposure × years	0.02	0.01	0.002	0.02	0.01	0.049
Random effects	**Estimate**	**SE**		**Estimate**	**SE**	
Subject: random intercept SD	10.89	0.57		10.89	0.57	
Subject: random slope SD	0.82	0.06		0.82	0.06	
Subject intercept–slope correlation	0.08	0.09		0.10	0.09	
Ear: random intercept SD	7.67	0.33		7.67	0.33	
Residual SD	3.97	0.05		3.98	0.05	

SE = standard error; SD = standard deviation.

6 kHz audiometric frequencies from the ISO 1999:2013 hearing loss model using both the L_{AVG} and L_{EQ} exposure metric to the 10th, 50th, and 90th percentiles of hearing loss at the same frequencies predicted by the mixed models with the baseline HTLs are presented in Supplementary Table S4, available at the *Annals of Work Exposures and Health* online. The predictions produced by the ISO model and mixed model were similar for both the L_{EQ} and L_{AVG} exposure metrics. However, in 14 out of the 18 comparisons (77.7%), the mixed model using the L_{EQ} exposure metric more closely matched the estimated hearing loss that was calculated by their corresponding ISO model, suggesting that the L_{EQ} performs slightly better than the L_{AVG} in predicting hearing loss in this cohort (see Supplementary Figure S1, available at the *Annals of Work Exposures and Health* online). Table 4 presents the differences between the 10th, 50th, and 90th percentiles of hearing loss at the same frequencies between the mixed models without the additional repeated measurements and the ISO 1999:2013 hearing loss model using both the L_{EQ} and L_{AVG} exposure metrics.

Figure 2 shows that for 13 out of 18 comparisons (72.2%), the L_{EQ} exposure metrics more closely matched the estimated hearing loss that was calculated by the ISO model. The mixed models using the L_{EQ} with the additional measurements were found to produce a better agreement with the ISO model than the mixed models with the baseline HTLs except for the 50th percentile of the 6-kHz test frequency and the 90th percentile of the 1- and 6-kHz test frequencies. Similarly, the mixed models using the L_{AVG} without the additional measurements were found to produce a better agreement with the ISO

Table 4. Comparison of estimated hearing loss using the L_{EQ} and L_{AVG} exposure metrics in the ISO hearing loss and mixed models without the baseline HTLs covariate.

Frequency (kHz)	L_{EQ}			L_{AVG}			Smallest difference
	Model	ISO	Difference (Model–ISO)	Model	ISO	Difference (Model–ISO)	
10th percentile							
0.5	1.62	−5.76	7.38	1.62	−5.76	7.38	Same
1	0.63	−5.61	6.24	0.64	−5.69	6.33	L_{EQ}
2	0.93	−6.34	7.27	0.91	−6.12	7.03	L_{AVG}
3	0.47	−6.53	7.00	0.47	−6.6	7.07	L_{EQ}
4	1.19	−5.88	7.07	1.19	−6.76	7.95	L_{EQ}
6	4.67	−8.56	13.23	4.68	−8.39	13.07	L_{AVG}
50th percentile							
0.5	6.11	0.85	5.26	6.12	0.85	5.27	L_{EQ}
1	5.39	1.69	3.70	5.4	0.97	4.43	L_{EQ}
2	6.5	2.18	4.32	6.47	1.66	4.81	L_{EQ}
3	7.25	4.83	2.42	7.26	2.66	4.60	L_{EQ}
4	8.25	6.66	1.59	8.23	3.64	4.59	L_{EQ}
6	13.33	5.99	7.34	13.34	4.12	9.22	L_{EQ}
90th percentile							
0.5	13.39	9.19	4.20	13.37	9.17	4.20	Same
1	17.36	9.47	7.89	14.01	9.37	4.64	L_{AVG}
2	18.26	13.21	5.05	24.06	11.65	12.41	L_{EQ}
3	22.45	13.99	8.46	22.45	12.57	9.88	L_{EQ}
4	33.34	15.70	17.64	33.35	13.74	19.61	L_{EQ}
6	36.12	16.42	19.70	36.11	14.59	21.52	L_{EQ}

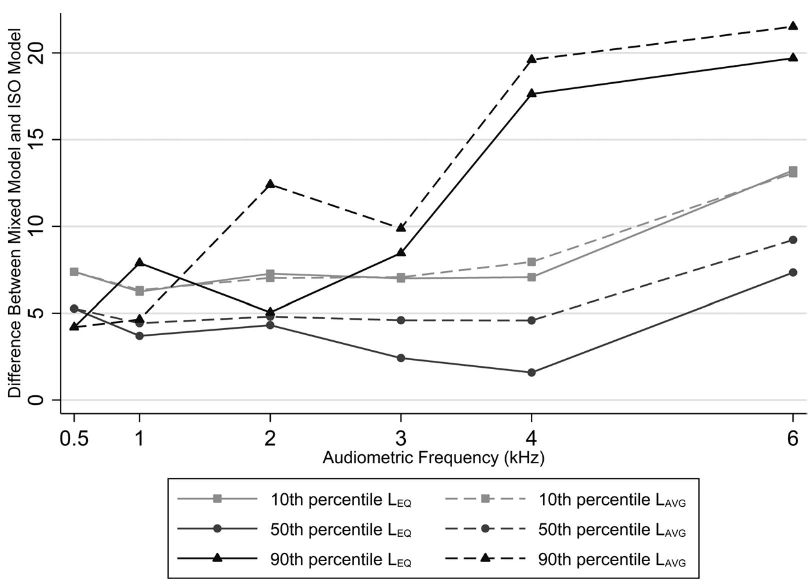

Figure 2. Difference between model (without baseline HTL covariate) and ISO predictions of hearing loss at the 10th, 50th, and 90th percentiles for the L_{EQ} and L_{AVG} metrics.

model than the mixed models including the baseline HTLs expect for the 50th percentile of the 6-kHz test frequencies and the 90th percentiles at the 2- and 6-kHz test frequencies.

Discussion

The debate on whether the L_{EQ} or L_{AVG} exposure metric is more predictive of NIHL risk is a controversial subject, and no single study will be able to conclusively settle this debate. However, this study suggests that the L_{EQ} is the more appropriate metric for predicting NIHL and provides a better foundation for developing exposure response relationships and providing guidance for the development of regulations and standards. One of the main strengths of our study is that it used a cohort of noise-exposed workers that were followed for approximately 10 years. This represents an exposure duration sufficient for NIHL to occur; in fact, the majority of loss expected over the course of a working lifetime in noise is predicted to occur within the first 10 years of exposure (ISO, 2013).

The first set of mixed models used in this analysis did not include a covariate for baseline HTLs. Instead, the baseline HTLs were considered as additional measurements in the model. This was done because audiometric tests have inherent variability and measurement error, as demonstrated by the statistically significant effect of the study phase on HTLs because of changes in equipment and operators (Karlsmose *et al.*, 1998). In addition, the causal relationship between noise exposure and hearing loss results in the inclusion of baseline HTLs in the model biasing the results toward the mean (Glymour *et al.*, 2005). The additional repeated measurements in the models without the baseline adjustment still allow for us to account for an individual subject's change in HTLs over time without biasing the relationship between the exposure and hearing outcomes. Because of this, we believe the models with the additional measurements are more appropriate than the models that control for baseline HTLs; however, we presented those models here to allow for comparison with the findings of Seixas *et al.* (2012).

The second set of mixed models used in this analysis allowed us to control several covariates including age, hearing levels at baseline, and the number of years exposed to noise during the study, all of which can impact HTLs. When comparing the mixed model using the L_{EQ} to the mixed model using the L_{AVG}, we found that the L_{EQ} model produced a lower AIC compared with the L_{AVG} model in at all test frequencies, indicating the L_{EQ} model had a better fit. However, the difference between the two models was generally small, and only three of seven test frequencies were found to have an AIC difference >2, i.e. a difference indicative of meaningfully different performance between the L_{AVG} and L_{EQ} models. It is worth noting that the 3- and 4-kHz test frequencies (along with 6 kHz) have been found to be most susceptible to NIHL (Royster *et al.*, 2003). In both L_{EQ} models, cumulative exposure was found to be a significant predictor of hearing loss at the 0.5-kHz frequency. This was not the case for either of the L_{AVG} models. Occupational noise exposure has not traditionally been associated with low-frequency hearing loss (e.g. at 0.5 kHz), and this may be a spurious finding. These results may also reflect potential issues with mobile audiometric van testing and possible masking effects associated with low-frequency background noise in the test environment.

When the 10th, 50th, and 90th percentiles of predicted hearing loss using the ISO model were compared to the same percentiles of predicted hearing loss from our mixed models with baseline HTLs, the L_{EQ} models showed better agreement. However, we found that in all cases, our mixed models predicted greater NIHL than the ISO models. This is likely due to the fact that a subset of workers in this cohort had already experienced hearing loss before enrollment. These workers tended to have worse and more variable hearing outcomes compared with those who enrolled in the study with less or minimal hearing loss. The ISO model provides no way for preexisting hearing loss to be factored into the NIHL predictions based on age and known noise exposure (ISO, 2013). When we compared the 10th, 50th, and 90th percentile of predicted hearing loss from the mixed models with the additional measurements, we again found that the L_{EQ} models showed better agreement with the ISO model than the L_{AVG} model, but overall the models without baseline HTLs had better agreement than the models with the baseline HTLs.

Recently there has been an increased interest in the impact of non-Gaussian noise—complex noise consisting of varying, intermittent, and interrupted exposures—on the risk and severity of NIHL. A recent contract report to NIOSH summarized the peer-reviewed literature and came to the conclusion that an exposure metric modified by a measure of kurtosis could provide a more accurate predictor of NIHL than simply the L_{EQ} or L_{AVG} alone (Suter, 2016). To evaluate this possibility, we compared the AICs of our L_{EQ} and L_{AVG} mixed models with an added variable for peakiness, using metrics previously developed and evaluated by Seixas *et al.* on the same cohort of construction workers (Seixas *et al.*, 2005a). Following the inclusion of the peakiness metric, the L_{EQ} model still demonstrated generally lower

AIC values compared with its equivalent L_{AVG} model, but the difference between AICs was reduced to <2 for all models (see Supplementary Table S2, available at the *Annals of Work Exposures and Health* online). The L_{EQ} was still a better fit in our model, but our finding that the inclusion of a measure of peakiness and resulting improvement in model fit suggests that a combination of the L_{EQ} and some sort of measure of kurtosis may further improve the model. Further research is needed to investigate the impact of including a measure of kurtosis on NIHL predictions. Our study only examined the effects of noise exposures in construction workers, who are exposed to intermittent noise, so these results may not be generalizable to occupational groups that are exposed to truly continuous noise or who have regular, scheduled breaks from exposure. There is limited evidence to support the notion that most occupations have such breaks, consistent with the rationale behind the L_{AVG} (Neitzel *et al.*, 1999; Suter, 2002). The high correlation between the L_{EQ} and L_{AVG} exposure measurements made on construction workers resulted in similar levels of model fit and predicted hearing outcomes. This was further complicated by the fact that many of the construction workers evaluated here had preexisting hearing loss. One set of mixed models controlled for this situation through the use of a categorical variable for baseline hearing level. The other set of mixed models instead used the baseline HTLs as additional measurements and excluded the fixed effect for baseline HTLs. Regardless, it is not possible to account for baseline hearing levels in the ISO model (ISO, 2013). This is likely the reason that our mixed models consistently predicted higher hearing thresholds than the ISO model and highlights an important weakness in the ISO model. Despite these drawbacks, we believe that the results of this study add to the growing body of evidence supporting the use of the L_{EQ} over the L_{AVG}.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

Conflict of Interest Declaration

The authors have no conflict of interest to disclose. However, in the spirit of full disclosure, the authors would like to make the editor aware that one of the authors (B.R.) is currently employed at Cardno ChemRisk, which is a scientific consulting firm involved with litigation. The research for this article was completed when the author was a doctoral student at the University of Michigan, and his current employment has no impact on this article.

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