Longitudinal Assessment of Noise Exposure in a Cohort of Construction Workers

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Objectives: To address questions surrounding noise-induced hearing loss (NIHL) from variable noise, we have been evaluating noise exposures and changes in hearing in a prospective cohort of construction workers (representing eight trades) and controls. In this paper, we develop and explore several long-term exposure estimates for cohort members.

Methods: We followed cohort members between 1999 and 2009 and interviewed them approximately annually to obtain a detailed work history for the previous subject-interval while also collecting tests of hearing sensitivity. Over the same period, we also collected a sample of full-shift average noise measurements and activity information. We used data from these two sources to develop various exposure estimates for each subject for specific subject intervals and for the duration of the study. These estimates included work duration, trade-mean (TM)-equivalent continuous exposure level (L_{EQ}), task-based (TB) L_{EQ}, a hybrid L_{EQ} combining TB and subjective information, and an estimate of noise exposure 'peakiness'.

Results: Of the 456 subjects enrolled in the study, 333 had at least 2 interviews and met several inclusion criteria related to hearing sensitivity. Depending on the metric used, between one-third and three-quarters of 1310 measured full-shift noise exposures exceeded permissible and recommended exposure limits. Hybrid and TB exposure estimates demonstrated much greater variability than TM estimates. Work duration and estimates of exposure peakiness showed poor agreement with average exposures, suggesting that these metrics evaluate different aspects of exposure and may have different predictive value for estimating NIHL.

Conclusions: Construction workers in the cohort had subject-interval and study-average exposures which present a substantial potential risk of NIHL. In a subsequent paper, we will use these estimates to evaluate the exposure–response relationship between noise and NIHL.

Keywords: construction; exposure assessment; exposure variability; noise

INTRODUCTION

Assessment of exposure in occupational epidemiological studies of chronic health effects presents numerous challenges. Few industries are associated with completely steady-state exposures, and the challenges associated with assessment of exposure and subsequent health effects increase dramatically with increasing exposure variability (Rappaport *et al.*, 1993; Kromhout and Heederik, 1995; Kromhout, 2002; Loomis and Kromhout, 2004). As a result, dynamic industries such as construction represent a particularly challenging setting for exposure assessment. Workers in these industries often do not have access to occupational health services (Snashall, 1990; Yu *et al.*, 2002), and industry employers have traditionally dedicated few resources to prevention of chronic health effects, focusing instead on more easily preventable acute hazards (Ringen *et al.*, 1995b). This has resulted in a lack of occupational protection for workers in these industries and high rates of occupational disease (Shilling and Brackbill, 1987; Ringen *et al.*, 1995a; Leigh and Miller, 1998; Bonauto *et al.*,

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2006). Construction workers have been shown to have high potential for overexposure to noise (LaBenz *et al.*, 1967; Utley and Miller, 1985; Greenspan *et al.*, 1995; Legris and Poulin, 1998; Blute *et al.*, 1999; Sinclair and Haflidson, 1995; Kock *et al.*, 2004) and also have high rates of noise-induced hearing loss (NIHL; Kenney and Ayer, 1975; Arndt *et al.*, 1996; Daniell *et al.*, 1998, 2002; Wu *et al.*, 1998; Meyer *et al.*, 2002; Suter, 2002; Dement *et al.*, 2005; Hong, 2005), a permanent and irreversible yet completely preventable disease. Noise exposure regulations (OSHA, 1983) have been in place in general industry for decades, but few US construction workers are covered by noise exposure regulations, and enforcement efforts have generally been lax (Reilly *et al.*, 1998; Jeffress, 2000). As a result, many construction workers needlessly suffer NIHL.

Despite the high incidence of NIHL among construction workers, questions remain regarding the progression of NIHL resulting from highly variable noise exposures. Existing models developed to predict NIHL given specific exposure level and duration inputs (ANSI, 1996) are based largely on studies of workers with non-time-varying exposures, and the applicability of these models to highly variable exposures is unknown. To address these questions, we have been evaluating noise exposure and changes in hearing in a prospective cohort of construction workers and controls in Seattle, WA. An initial cohort of 456 subjects was followed from 1999 to 2004, during which time subjects were interviewed annually and given a battery of hearing tests (Seixas *et al.*, 2005b). One-hundred thirty-five members of the initial cohort participated in the second stage of the study (2005–2009) and continued participation in subsequent annual interviews and hearing tests. Eight trades are represented in the cohort: carpenters, cement masons, electricians, insulation workers, ironworkers, masonry workers, operating engineers, and sheet metal workers. Construction subjects were recruited from apprenticeship programs, and controls were students recruited from graduate and professional degree programs at the University of Washington.

A sustained campaign of exposure measurements on cohort members was infeasible due to cost and logistical complexities. Therefore, alternative methods for creating exposure estimates were needed. We have previously developed and evaluated a number of exposure assessment metrics, including use of trade-mean (TM) exposure levels (Neitzel *et al.*, 1999), task-based (TB) exposure levels (Seixas *et al.*, 2003), subjective rating (SR) of exposure (Neitzel *et al.*, 2009), hybrid metrics combining estimates from these single metrics (Neitzel *et al.*, 2011a), and metrics intended to assess exposure variability (Seixas *et al.*, 2005a). We have validated these metrics for estimation of short-term exposures ranging from a single shift to several months (Neitzel *et al.*, 2011a, 2011b). Here we expand on our earlier efforts by using these metrics to develop long-term exposure estimates for the entire multiyear period the cohort was monitored, as well as specific subject-intervals within that period. The relationship between the exposure estimates described here and the measurements of hearing damage among cohort members will be described in subsequent articles.

METHODS

Data collection

Exposure estimates derived here were based on two primary sources of data: dosimetry measurements and questionnaire data. The first data source was measurement of full-shift noise exposures on a sample of construction workers not enrolled in the cohort. We used these measurements to predict noise levels associated with different construction trades and tasks. The second source of information was cohort members' self-reported work activities and behaviors obtained through the administration of questionnaires. Questionnaires covered the period since the subject's prior interview, a period we will henceforth refer to as a 'subject-interval', with the duration of a subject-interval being the time in years between interviews. By combining the dosimetry and questionnaire data, we were able to estimate exposures to noise using five different metrics: duration of noisy work, equivalent continuous average levels (L_{EQ}s) based on TM, TB, and SR information, and an impulsiveness or 'peakiness' metric.

Dosimetry data. From 1997 to 2008, we collected full-shift noise measurements on a sample of over 75 commercial and heavy construction sites in the Puget Sound region of Washington state. Due to difficulties in identifying and gaining access to construction sites on which cohort members were employed, only a small fraction of measurements (<5%) were on cohort members. No direct measurements were made on controls, who were either in school or working in quiet professional or clinical environments during the study. The sample of commercial and heavy construction sites at which measurements were collected is broadly representative of the sites at which cohort members were employed based on working locations and conditions reported by each cohort member for each subject-interval.

We have described our measurement methodology previously (Neitzel *et al.*, 2011a). Briefly, we used datalogging noise dosimeters (Q-300 and NoisePro DLX; Quest Technologies—a 3M Company, Oconomowoc, WI, USA) configured to measure on two channels using measurement parameters specified by the US Occupational Safety and Health Administration (OSHA: 80 dBA threshold, 90 dBA criterion level, 5 dBA time–intensity exchange rate; OSHA, 1983) and the US National Institute for Occupational Safety and Health (NIOSH: 80 dBA threshold, 85 dBA criterion level, 3 dB exchange rate; NIOSH, 1998). During each minute of measurement, dosimeters measured average (OSHA L_{AVG} and NIOSH L_{EQ}) and maximum (L_{MAX}) levels using the A frequency-weighting network and a SLOW response time. Subjects wearing dosimeters simultaneously logged the tasks they performed and their use of hearing protection devices (HPDs) over the course of the measured shift using an activity card. Tasks and HPD use were recorded with ∼15-min time resolution, allowing this information to be aligned with levels measured by the noise dosimeters.

Questionnaire data. Cohort members were seen on a nominally annual basis by research staff. During these interviews, research staff administered a questionnaire to each subject that included a wide variety of health- and work-related items. Construction subjects were asked to summarize, for each job held since the previous interview, tasks they had performed (and how often they had performed each reported task), use of HPDs, and subjective perceptions of noise exposure using a validated survey item (Neitzel *et al.*, 2009, 2011a). Reporting occurred for each job held during each subject-interval to account for variations in tasks and HPD use between jobs and to assist workers in chronologically reconstructing their subject-interval exposure history. Both construction and control subjects were asked to report noisy non-construction work since the previous interview (which justified our presumption of otherwise quiet work among controls), as well as use of HPDs and subjective perceptions of noise exposures during this work.

Treatment of HPD use. Two sources of HPD use data were available for potential use in this study: HPD use reported during dosimetry measurements and HPD use reported via questionnaire. However, both these sources of data have important limitations (Neitzel and Seixas, 2005; Trabeau *et al.*, 2008; Edelson *et al.*, 2009; Griffin *et al.*, 2009), and we have elected to exclude consideration of HPDs in this article.

Data analysis

Dosimetry data. Dosimetry data were cleaned to correct untenable data, as described elsewhere (Seixas *et al.*, 2005a). One-minute noise levels were merged with activity card task information to create a data set of task-specific noise levels in an MS Access (Microsoft, Redmond, WA, USA) database and exported for statistical analysis (Intercooled Stata 10.0; Statacorp LP, College Station, TX, USA).

We assessed full-shift dosimetry exposure levels (dBA) and task-specific levels using the L_{EQ} and L_{AVG} metrics. L_{EQ} exposures were computed for individual i on shift j as:

$$L_{EQij} = 10\log_{10}\left[\frac{1}{M_{ij}}\sum_{k=1}^{n_{ij}} 10^{L_{ijk}/10}\right], \qquad (1)$$

where L_{ijk} are the 1-min average L_{EQ} levels measured over $k = 1$ to n_{ij} min, and M_{ij} is the total number of minutes measured in the shift (Earshen, 2000). We computed L_{AVG} exposure levels similarly, replacing the factor '10' with '16.61' (Earshen, 2000).

We assessed variability in measured noise levels using two metrics (Seixas *et al.*, 2005a). Peakiness at the workshift level was summarized as the average ratio of the L_{MAX} to L_{EQ} levels across the minutes within the shift, as shown in equation (2).

$$\left[L_{MAX}/L_{EQij}\right] = \frac{1}{M_{ij}}\sum_{k=1}^{n_{ij}} \frac{10^{L_{MAXijk}/10}}{10^{L_{EQijk}/10}}. \qquad (2)$$

In addition to computing this metric at the workshift level, we computed task-specific ratios in a similar manner for each task on which we had measurement data.

Calculation of exposure metrics. Four different exposure assessment metrics were used to develop exposure estimates for each member of the cohort for each subject-interval and across all subject-intervals (e.g. for the entire study). These metrics were duration of exposure to noise, TM exposure, TB exposure, and a hybrid exposure based on a combination of TB and SR exposures.

Duration of work in noise: Duration of noisy work represents the simplest possible quantitative estimate of exposure. For construction subjects, work duration was computed as the sum of hours worked in construction and noisy non-construction jobs within each subject-interval. Control subjects and construction subjects reporting no construction or noisy non-construction work in a subject-interval were assigned zero annual hours of exposure for that subject-interval.

Trade-mean exposure estimates: We developed TM exposure estimates by computing the mean full-shift L_{EQ} for all individuals within each trade for

which we had noise measurement data. We then assigned this TM exposure to each individual in the trade. Due to large variations between trades in the number of hours worked per year, and in subject-interval lengths, we normalized each subjects' TM exposure to 2000 working hours per year. This approach effectively assumed that the noise energy to which a subject was exposed in a given subject-interval was delivered over a 2000-h exposure period annually. We accomplished this for each individual i using equation (3):

$$L_{EQij,TM2000} = 10\log_{10}\left[\frac{1}{2000 \times Y_{ij}}\Big[\big(H_{Cij} \times 10^{L_{TM}/10}\big) + \big(H_{NCij} \times 10^{L_{NC}/10}\big)\Big]\right],$$ (3)

where L_{TM} is the TM noise level, H_{Cij} is the number of hours worked in construction during subject-interval j, L_{NC} is an assigned noise level of 85 dBA for reported noisy non-construction work, H_{NC} is the number of hours worked at noisy non-construction jobs, 2000 h is fixed as the duration of a standard work year, and Y is subject-interval length in years. Control subjects and construction workers who did not report any construction or noisy non-construction work in a subject-interval were assigned a nominal work duration of 2000 h and L_{TM} exposures of 70 dBA, a level at which no hearing loss is expected (EPA, 1978).

Task-based exposure estimates: We developed TB estimates using 'trade/task events' as the basic unit of analysis (Seixas *et al.*, 2005a). We defined trade/task events as the average exposure during all periods of time within a single measured workshift that an individual subject reported a single task. We computed mean L_{EQ} levels L for each trade/task as the arithmetic average of the L_{EQ} for each trade/task event across all subjects who reported that trade/task. We then computed total time-at-task for all T tasks reported by each construction subject in a subject-interval and created TB exposure predictions using equation (4) (Seixas *et al.*, 2005a). As with TM exposure estimates, we normalized our TB exposure estimates to 2000 annual working hours:

$$L_{EQij,TB2000} = 10\log_{10}\left[\frac{1}{2000 \times Y_{ij}}\Bigg(\bigg(\sum_{t=1}^{T} H_{ijt}10^{L_t/10}\bigg) + \big(H_{NCij} \times 10^{L_{NC}/10}\big)\Bigg)\right],$$ (4)

where L_t is the mean L_{EQ} level for trade/task t and is applied to the period H_{ijt} in which that trade/task was reported for H hours by individual i in subject-

interval j. The variables H_{NC}, Y, and L_{NC} are identical to those used in equation (3).

Hybrid exposure estimates: We developed hybrid estimates based on a linear regression metric described previously (Neitzel *et al.*, 2011b). Briefly, this metric combines subjects' $L_{EQij,TB2000}$ (equation 4) with estimates developed using subjects' SRs of their noise exposures using equation (5):

$$L_{EQij,SR2000} = 10\log_{10}\left[\frac{1}{2000 \times Y_{ij}}\bigg(\sum_{r=1}^{R} H_{ijr}10^{L_r/10}\bigg)\right],$$ (5)

where L is the mean L_{EQ} level associated with category r of a perceived SR noise intensity item with three possible response categories (described in detail in [Neitzel *et al.*, 2011a]) and is applied to the work duration H_{ijr} for which that response was reported by individual i in subject-interval j. The variable Y is identical to those used in equation (3).

We created hybrid $L_{EQij,H2000}$ estimates using the regression model shown in equation (6). The coefficients in this equation come from our earlier study of 4-month average exposures measured in a cohort of 68 construction workers (Neitzel *et al.*, 2011b) and were developed by regressing TB and SR estimates created for those workers on their measured mean exposures.

$$L_{EQ_{ij},H2000} = -137.4 + 0.5\big(L_{EQ,ijTB2000}\big) + 2.0\big(L_{EQ,ijSR2000}\big).$$ (6)

Peakiness estimates: We estimated the peakiness of construction exposures for each subject-interval using task-specific L_{MAX}/L_{EQ} ratios. We developed these estimates by computing time-weighted arithmetic average variability metrics across all T tasks reported over H hours by subject i in subject-interval j:

$$\big[L_{MAX}/L_{EQij}\big] = \frac{1}{H_{ij}}\sum_{t=1}^{T}\big(H_{ijt} \times L_{MAX}/L_{EQt}\big). \quad (7)$$

Control subjects were assigned a peakiness value of 1. Due to a lack of measurement data, we did not estimate peakiness for reported noisy non-construction work.

Data analysis

We conducted descriptive analyses of the measured full-shift noise exposures using the L_{EQ} and L_{AVG} average metrics as well as the L_{MAX}/L_{EQ} peakiness metric. We also visually evaluated trends in

full-shift noise exposures over time. We computed descriptive statistics for exposure within each subject-interval and across all subject-intervals using our five metrics: duration of noisy work, TM L_{EQ}, TB L_{EQ}, hybrid L_{EQ}, and peakiness. Finally, we computed the coefficient of determination (R^2) between estimates from each of the five metrics to evaluate the association between the metrics and produced graphical plots to visually compare these relationships.

RESULTS

Cohort description

Three-hundred and thirty-three subjects were included in this analysis. Criteria for inclusion were at least two complete interviews and adequate hearing test data. Subject characteristics will be described in detail in a later paper. Briefly, 274 subjects (82%) were construction workers, and the remaining 59 were controls. The number of subjects in the eight participating trades ranged from 13 insulation workers to 66 masonry workers; the mean number of subjects per trade was 34 ± 21. The age distributions across the two groups were similar though more construction subjects were 18–20 years old (12 vs. 0%), and more control subjects were 21–25 years old (45 vs. 33%). Attrition over time was quite similar in both groups, with ~25% of subjects having two follow-ups over the study period, declining to ~10% with four follow-ups, and 5% with seven. The study period was comprised of 1298 subject-intervals, of which 1062 were contributed by construction subjects.

Dosimetry data

Table 1 presents the summary results of our 1310 full-shift noise dosimetry measurements. About one-third of measured workshifts exceeded the OSHA Action Limit (OSHA, 1983) of 85 dBA L_{AVG}, while nearly three-quarters of measured workshifts exceeded the 85 dBA L_{EQ} NIOSH Recommended Exposure Limit (NIOSH, 1998). Ironworkers had the highest full-shift L_{EQ} and L_{AVG} levels, and insulation workers had the lowest levels. The trades with the greatest and least exposure peakiness (e.g. highest L_{MAX}/L_{EQ} ratio) were ironworkers and operating engineers, respectively. Figure 1 presents dosimetry levels over time. No temporal trend was noted in these exposures, suggesting that noise levels did not change over this period. No trends in noise levels were seen over time for any of the trades assessed or for the two types of construction projects assessed (commercial and heavy construction).

Subject-interval noisy work durations

Table 2 describes the duration of work by subject-interval. Ninety-five percent of all construction subject-intervals included construction work. Construction subjects worked, on average, <2000 h per year. The variability in hours worked per year was quite large across trades. Operating engineers and sheet metal workers approached 2000 h of work per year on average, while carpenters worked nearly 20% fewer hours per year on average. Some trades were seen more frequently than others: e.g. sheet metal workers, insulation workers, and ironworkers had an average subject-interval length of 1.3 years, compared to 1.8 years for operating engineers. Two of the trades with the highest TM exposure

Table 1. Full-shift average exposure levels by trade

| Trade	n measurements	L_{AVG} (dBA)			L_{EQ} (dBA)			Peakiness of exposure (L_{MAX}/L_{EQ})	
		Mean	SD	% >85 dBA	Mean	SD	% >85 dBA	Mean	SD
Construction workers	1310	82.6	5.3	33.2	88.1	5.5	72.6	53.1	23.1
Carpenter	532	83.7	4.6	41.7	89.4	4.8	84.2	63.3	25.7
Cement mason	55	82.3	5.9	38.2	87.3	6.7	67.2	37.5	14.7
Electrician	303	80.4	5	16.8	86.2	5.4	56.8	47.5	14.1
Insulation worker	22	76.1	3.9	4.6	81.1	3.3	18.1	46.1	13.6
Ironworker	118	84.4	5.1	48.3	90.1	5.6	86.4	58.9	21.2
Masonry worker	86	82.4	7.1	33.7	87.9	7.4	62.8	46.4	19.8
Operating engineer	115	84.1	5.3	39.1	88.2	4.8	77.4	34.9	13.6
Sheet metal worker	79	80.5	4.2	11.4	85.9	4.9	57	49.3	21.1
Controls	—	70	—	0	70	—	0	1	—
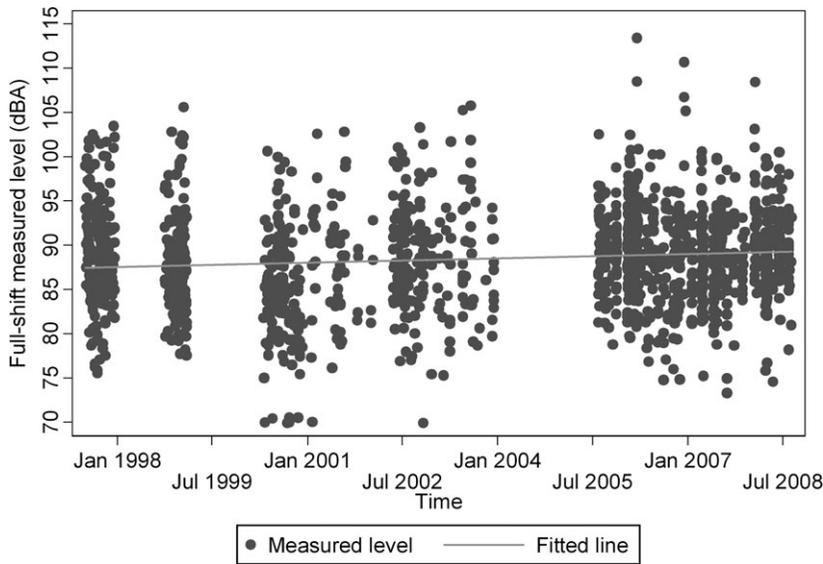
Fig. 1. Full-shift dosimetry measurements over time ($n = 1310$ measurements).

Table 2. Work exposure durations by subject-interval

Trade	n subject-intervals	Subject-interval duration (years)		Subject-interval noisy work hours		Noisy work hours per year			% Intervals with construction work
		Mean	SD	Mean	SD	Rank	Mean	SD	
Construction workers	1062	1.4	1.1	2627	2465	—	1747	757	94.9
Carpenter	252	1.5	1.3	2614	2524	8	1612	800	89.7
Cement mason	98	1.6	1.5	2762	3104	7	1637	782	94.9
Electrician	76	1.4	1.1	2309	1660	5	1720	702	96.1
Insulation worker	60	1.3	0.9	2490	1988	4	1837	630	98.3
Ironworker	180	1.3	0.9	2469	2090	3	1841	746	93.9
Masonry worker	239	1.4	0.9	2531	2466	6	1696	790	92.5
Operating engineer	68	1.8	1.1	3647	3416	1	1992	882	100
Sheet metal worker	89	1.3	1.1	2677	2062	2	1974	332	98.9
Controls	236	1.3	0.9	0	0	—	0	—	0

levels (operating engineers and ironworkers, Table 1) also had among the longest annual work durations in Table 2.

Very few construction subjects (ranging from 0 insulation workers to 7 carpenters, representing 12% of workers in that trade) and no control subjects reported any noisy non-construction jobs (data not shown). Among the construction subjects reporting noisy non-construction work, the mean duration of work per subject-interval was 531 h (range 60–1537 h). Overall, the contribution of noisy non-construction work to overall noise exposures was zero for control subjects and negligible for the vast majority of construction workers.

Subject-interval exposures

Table 3 compares individual subject-interval L_{EQ} exposure estimates developed using the TM, TB, and hybrid metrics, as well as the peakiness (L_{MAX}/L_{EQ}) estimate. The ranking of trades was reasonably consistent for some trades across the three L_{EQ} metrics—e.g. electricians and insulation workers were always the lowest exposed trades, and operating engineers were always the highest. The mean exposure estimates were also generally within 1–2 dBA across the metrics, though the difference in means for operating engineers spanned $\sim$5 dBA between the TM and hybrid metrics. The variability in exposure estimates was always smallest for the TM

Table 3. Estimated subject-interval L_{EQ} levels (dBA) and 'peakiness'

Group	n subject-intervals	Exposure level (dBA)									Peakiness (L_{MAX}/L_{EQ})		
		$L_{EQ,iTM2000}$			$L_{EQ,iTB2000}$			$L_{EQ,iH2000}$					
		Rank	Mean	SD	Rank	Mean	SD	Rank	Mean	SD	Rank	Mean	SD
Construction workers	1062	—	86.2	4.9	—	86.2	5.4	—	86.3	7.2	—	51.8	21.7
Carpenter	252	3	86.7	5.8	4	86	5.8	4	85.9	7.2	3	54.4	23.5
Cement mason	98	6	85.5	3.7	5	85.1	5.6	5	85.2	6.3	7	42.3	14.8
Electrician	76	7	84.3	5.3	7	83.6	6	7	82.2	7.4	4	49.3	14
Insulation worker	60	8	80.3	2.2	8	81.3	2.9	8	80.8	3.7	6	46.8	9
Ironworker	180	1	88.5	4.9	2	88.7	5.1	2	90.5	7.3	1	63.2	24.5
Masonry worker	239	4	86.2	4.3	6	85	4.5	5	85.2	6.5	5	47.3	19.8
Operating engineer	68	2	87.7	2.5	1	89.2	4.4	1	92.2	6.6	8	40.5	14.4
Sheet metal worker	89	5	85.7	1.8	3	86.6	3.7	3	86.3	4.2	2	58.4	24.9
Controls	236	—	70	—	—	70	—	–	70	—	—	—	—

metric and largest for the hybrid metric. In some cases, the hybrid estimate standard deviations were twice as large as the TM estimate, indicating greater variability in estimated exposures. The peakiness metric produced very different rankings among the trades than did the other three exposure assessment metrics. Ironworkers had the highest L_{MAX}/L_{EQ} ratio—consistent with their ranking from the other metrics—but operating engineers, who had among the highest mean L_{EQ2000} exposures, had the lowest mean L_{MAX}/L_{EQ} ratio.

Study average exposures

Table 4 presents study-average L_{EQ} and peakiness metric results across all 333 subjects. The average duration of study involvement was similar between construction workers and controls—about 5.5 years. The difference between study average exposure estimates for the construction workers was ~2 dBA across the TM, TB, and hybrid estimates, with the hybrid estimates again showing nearly twice the variability of the TM estimates. Study-average exposures were slightly higher than subject-interval exposures due to the logarithmic nature of noise dose accumulation.

Figure 2 is complementary to Table 4 and shows the distribution of the five exposure metrics. The association between the various exposures was generally poor to moderate, and even the two most closely associated metrics, the TB and hybrid L_{EQ}s, showed substantial differences.

DISCUSSION

We estimated exposures for a longitudinal cohort of construction and control subjects using exposure

assessment metrics ranging from simple (work duration) to complex (a hybrid approach incorporating TB and SR information and a separate metric for peakiness of exposure). The noise measurement data used in creating these estimates suggest that noise levels on commercial and heavy construction sites do not appear to be declining over time. A substantial fraction of workshifts—between one-third and three-quarters, depending on the averaging metric used—exceeded a full-shift average exposure of 85 dBA. The construction trades evaluated in this study showed large variability in the amount of hours worked per year, necessitating the normalization of exposure estimates to a 2000-h annual exposure period. Hybrid and TB exposure estimates had much greater variability than TM estimates, demonstrating that these metrics captured exposure variability better than did estimates based on subjects' trades. Work duration and peakiness showed poor agreement with average exposure, suggesting that these metrics evaluate different aspects of exposure, and highlighting the value of using multiple metrics to observe different aspects of exposure which may contribute to risk. The subject-interval and study-average noise exposure levels estimated here, which generally exceeded recommended exposure limits, suggest that most construction workers are at risk of NIHL following chronic exposure.

Our finding that measured full-shift noise levels in commercial and heavy construction did not appear to decline between 1998 and 2008 is contrary to some perceptions within the industry. It is also counter to recent literature which shows that other types of exposures, including exposures to airborne particulate (Vermeulen *et al.*, 2000; van Tongeren *et al.*, 2000; Spee *et al.*, 2007), dermal hazards (Vermeulen

Table 4. Duration of study participation and five study-average metrics of exposure

Exposure	Construction subjects ($n = 274$)		Control subjects ($n = 59$)		Whole cohort ($n = 333$)	
	Mean	SD	Mean	SD	Mean	SD
Duration (years)	5.5	3.4	5.3	3.2	5.4	3.4
Noisy work hours	10185	7204	0	—	8315	7446
L_{EQ}						
TM	87.1	2.9	70	—	84.1	7.1
TB	87.3	3.6	70	—	84.2	7.3
Hybrid	88.9	4.6	70	—	85.5	8.3
Peakiness	49	12.9	1	—	40.1	22
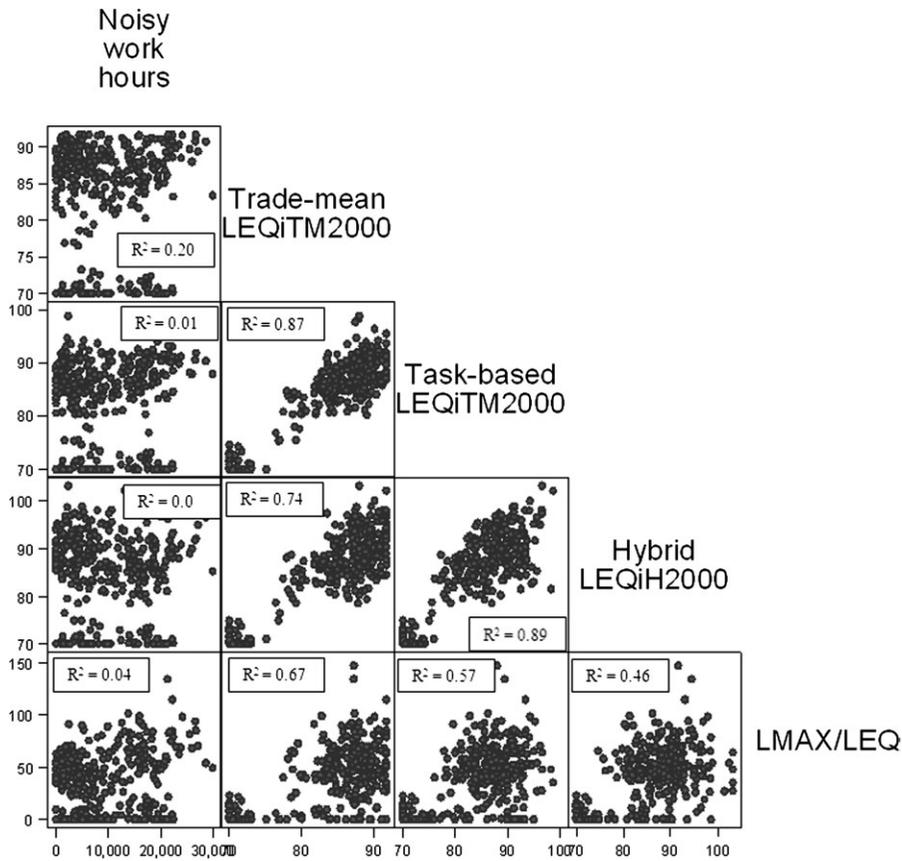
Fig. 2. Five study-average exposure metrics for cohort ($n = 333$ subjects).

et al., 2000), and even noise in some fixed industries (Davies et al., 2009) has been declining over time. The generalizability of this finding must be considered in light of the fact that the observation period, while reasonably long (10 years), is still of a limited duration and that the observations made do not encompass the totality of construction operations. For example, no measurements were made on residential or marine construction sites. Nevertheless, our results suggest that additional noise control measures are warranted in the construction industry.

No other studies estimating long-term average noise exposures among construction workers appear to have been published in the peer-reviewed literature. However, the TM levels estimated from the measurement data are consistent with levels published previously for workers in the USA (Greenspan et al., 1995; Blute et al., 1999; Suter, 2002), Canada

(Sinclair and Haflidson, 1995; Legris and Poulin, 1998), and European countries (Utley and Miller, 1985; Kock *et al.*, 2004), suggesting that at least the measurement data presented here are broadly generalizable.

In addition to the peakiness metric described here, we have previously described a metric intended to capture exposure variability (Seixas *et al.*, 2005a). This variability metric is computed as the ratio of L_{EQ}/L_{AVG}. We computed that metric using the dosimetry data presented here and found the L_{MAX}/L_{EQ} and L_{EQ}/L_{AVG} metrics to be very highly correlated (Pearson correlation coefficient 0.91, $P < 0.0001$). We therefore presented only the L_{MAX}/L_{EQ} results. However, the average exposure and peakiness estimates presented here are not well correlated and clearly capture different aspects of exposure (Fig. 2). There may be benefit to considering both types of estimates in combination, and we will explore combinations of these estimates in a subsequent paper evaluating the exposure–response relationship between noise and NIHL.

The majority of previous studies of NIHL among construction workers have evaluated NIHL in a cross-sectional sample of workers, with no attempt at exposure assessment beyond previous work in a construction trade (LaBenz *et al.*, 1967; Kenney and Ayer, 1975; Colvin *et al.*, 1998; Wu *et al.*, 1998; Kerr *et al.*, 2003; Hong, 2005). Where exposure estimates have been produced, they have relied on simple metrics of exposure, such as work duration (Hessel, 2000; Dement *et al.*, 2005). We believe that the more sophisticated assessment metrics presented here represent an important contribution to understanding the risk of NIHL in construction work.

This study had a number of limitations. The first is the lack of direct measurements on cohort members. This is less of a problem for construction subjects, for whom substantial measurement data were available from outside the cohort, than it is for control subjects, for whom no measurement data were available. It is likely that the majority of control subjects, who perform medical and professional work, have annual exposures of 70 dBA or less. However, some control subjects may have experienced occasional unassessed occupational exposures to high noise during the study period. This introduces potential misclassification of exposure, which could influence the analyses of the exposure–response relationship between noise and NIHL which will we present in future papers. Even with some misclassification, however, the large exposure differential between controls, who are extremely unlikely to have study-average occupational exposures in excess of 80

dBA, and construction subjects, who on average have study-average exposures in excess of 87 dBA (Table 4), should allow sufficient power to evaluate the exposure–response relationship.

The second study limitation concerns use of HPDs. We were not able to identify a metric which would allow for integration of HPDs into our exposure estimates since we have shown that use of trade-average HPD information collected using our validated dosimetry-based method (Neitzel *et al.*, 1999; Reeb-Whitaker *et al.*, 2004) has essentially no effect on our exposure estimates (Neitzel and Seixas, 2005), and we have little confidence in self-reported HPD use information collected via questionnaire based on our earlier findings (Neitzel and Seixas, 2005; Trabeau *et al.*, 2008; Edelson *et al.*, 2009; Griffin *et al.*, 2009). Despite the lack of an adequate means of considering HPD use, it is necessary to acknowledge that at least a fraction of workers are likely to achieve substantial reductions in exposure through the routine (and correct) use of HPDs. To address this problem, we will include self-reported HPD use as a separate predictor variable in models exploring the relationship between noise exposure and NIHL in a future paper. We will also perform a subanalysis of this relationship restricted only to subjects who reported never using HPDs as this appears to be the only self-reported use category that correlates well with observed use (Neitzel and Seixas, 2005).

The third study limitation relates to the length of time covered by the exposure estimates presented here. We have previously validated the accuracy of exposure estimates made with the techniques used here over shorter periods for time—e.g. over periods as long as 4 (Neitzel *et al.*, 2011a, 2011b) to 6 (Reeb-Whitaker *et al.*, 2004) months. However, given the multiple sources of error in the estimates presented here—variability in exposure due to changing conditions and subject recall of work activities being perhaps the two largest—it is likely that the accuracy of the current estimates is worse than the 2–3 dBA we have estimated previously (Neitzel *et al.*, 2011a).

CONCLUSIONS

With this paper, we have demonstrated that construction workers have substantial long-term average exposures to noise regardless of the assessment metric employed. We have also created the foundation for subsequent papers which will evaluate the relationship between the exposure estimates presented here and measured hearing damage among the study

subjects. Four of the exposure estimates presented here—work duration, TB and hybrid $L_{EQij2000}$ average, and peakiness (L_{MAX}/L_{EQ})—will be evaluated in subsequent papers. We do not have any 'gold standard' measures of exposure for the cohort against which these estimates of exposure can be compared, but based on our previous findings (Neitzel *et al.*, 2011b), we expect the hybrid approach, which captures the largest variability in estimated exposures, to demonstrate the greatest accuracy and to be the best predictor of NIHL.

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