AMERICAN INDUSTRIAL HYGIENE ASSOCIATION JOURNAL 60:807–817 (1999) Ms. #022

An Assessment of Occupational Noise Exposures in Four Construction Trades

Richard Neitzel
Noah S. Seixas
Janice Camp
Michael Yost

Department of Environmental Health, Box 354695, University of Washington, Seattle, WA 98195-4695

Three hundred thirty-eight noise exposure samples were collected from 133 construction workers employed in 4 construction trades: carpenters, laborers, ironworkers, and operating engineers. Four sites using a variety of construction techniques were sampled at least 12 times on a randomly chosen date over a 22-week period. Up to 10 volunteer workers were sampled for an entire work shift on each sampling day using datalogging noise dosimeters, which recorded both daily time-weighted averages (TWAs) and 1-min averages. Workers also completed a questionnaire throughout the workday detailing the tasks performed and tools used throughout the day. Regression models identified work characteristics associated with elevated exposure levels. Comparisons were made between exposures measured using the Occupational Safety and Health Administration (OSHA) exposure metric and the 1996 draft National Institute for Occupational Safety and Health/International Organization for Standardization (NIOSH/ISO) metric to examine the effects of differing exchange rates and instrument response times on construction noise exposures. The mean OSHA TWA for 338 samples was 82.8 dBA±6.8 dBA, whereas the mean NIOSH/ISO TWA for 174 samples was 89.7 dBA±6.0 dBA. Forty percent of OSHA TWAs exceeded 85 dBA, and 13% exceeded 90 dBA, the OSHA permissible exposure limit. The tasks and tools associated with the highest exposure levels were those involving pneumatically operated tools and heavy equipment. Trade was a poor predictor of noise exposure; construction method, stage of construction, and work tasks and tools used were found to be better exposure predictors. An internal validation substudy indicated excellent agreement between worker self-reporting and researcher observation. These data provide substantial documentation that construction workers in several key trades are frequently exposed to noise levels that have been associated with hearing loss, and demonstrate the need for targeted noise reduction efforts and comprehensive hearing conservation programs in the industry.

Keywords: construction noise, dosimetry, exposure assessment

Noise exposure has been recognized as a causal factor in hearing loss for many hundreds of years. Noise-induced hearing loss (NIHL) claims cost the U.S. hundreds of millions of dollars annually.(1) Workers suffering from NIHL are denied the ability to converse normally with others and are endangered in the work environment, as their ability to perceive audible warnings is seriously compromised.(2) NIHL also has been associated with other potential problems, such as balance dysfunction.(3) Workers in the construction industry are at particularly high risk; several studies have identified NIHL in 16–50% of construction workers,(4–6) and several nations have identified NIHL as one of the most common diseases in the construction industry.(7–9) The National Institute for Occupational Safety and Health (NIOSH) estimates that 15.8, 15.6, and 24.0% of U.S. construction workers employed by general building contractors, special trade contractors, and heavy construction (other than

Partial funding for this project was provided by the Center to Protect Workers' Rights through Small Study Grant 97–4-PS.

building) contractors, respectively, are exposed routinely to noise levels at or above 85 dBA,(10) for a total of 420,996 exposed workers. However, these figures were extrapolated from an occupational exposure survey performed in the early 1980s, and may not accurately reflect current employment or exposure levels. Furthermore, construction workers are often poorly informed about the risks of noise exposure and NIHL.(11)

Noise levels on construction sites range from 80–120 dBA around heavy equipment, whereas the noise levels measured around power tools used for smaller tasks range from 87–115 dBA.(4,12–15) Construction site noise contours indicate that large portions of construction sites may have sound levels over 85–90 dBA.(13–14) Existing noise dosimetry data indicate that time-weighted average (TWA) levels on construction sites can range from 74–105 dBA.(14,16–18) Construction workers working on or around heavy equipment have particularly high noise exposures.(13,15,17–18)

Sound level meter (SLM) readings, used in most of the existing studies, depend on the skill level of the meter's operator,(19) making comparisons between SLM-based studies somewhat uncertain. This is a notable deficit in available data on the construction industry. SLM data can be very useful for determining areas of construction that deserve further attention, and integrating SLM measurements can provide valid estimates of personal exposure to variable noise levels when used according to task-based assessment protocols;(20–21) however, few of the existing studies appear to meet these protocols. Dosimetry offers a more dependable method of determining the contribution of the individual pieces of equipment to average exposure levels, reducing the possibility of error stemming from relative operator skill and extrapolation of instantaneous readings to a shift-long average level.

One issue that arises with dosimetry is the exchange rate (ER) that should be used in calculating noise exposures. ER is the number of decibels required to double (or halve) the allowable exposure time, and is used in noise dose calculations: for instance, for every halving of exposure time (below the 8-hour criterion level, which equates to a 100% dose), the allowable sound pressure exposure level increases by the value of the ER. Studies performed in the United States involving dosimetry have utilized a 5 dB ER; little work has been done to characterize exposures using a more protective 3 dB ER, and no construction-specific studies have directly compared the two. Much of the TWA data are based on partial-shift monitoring, an approach with clear limitations given the intrashift task variability inherent in construction work. Also, generalizeability of the existing studies is limited due to the small number of sites and trades that have been examined.

While the existing studies indicate that construction workers have the potential for exposure to levels of noise that exceed established occupational exposure limits, there is a paucity of comprehensive noise exposure studies. This study offers a broader perspective on exposures, utilizing datalogging dosimeters combined with task/tool activity information to assess exposure levels among a large cohort at several sites and in different trades. It also provides a comparison between exposure levels measured according to several different exposure metrics utilizing different ERs and criterion levels.

METHODS

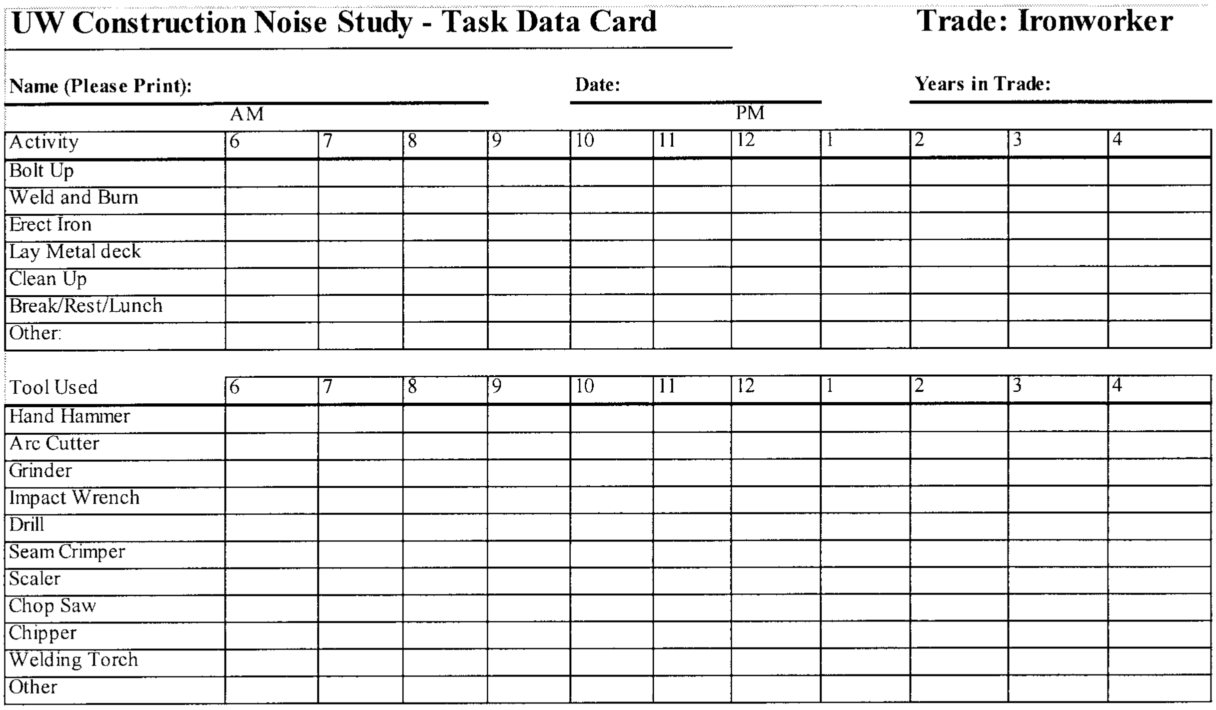
Intensive noise monitoring was performed on construction workers employed by a major (400+ employee) general contractor in the state of Washington. Preliminary meetings with company safety and health representatives allowed for identification of four primary trades employed by the company that were likely to encounter significant noise levels: carpenters, laborers, ironworkers, and operating engineers.

Four sites having the potential for continuous construction activity for the entire duration of the data collection period were chosen. Site A, a six-floor, 187,192 ft^2 public performance hall, involved cast-in-place, tilt-up, and precast concrete construction techniques. Site B, a five-floor, 331,446 ft^2 commercial office building, and Site D, a five-floor, 157,572 ft^2 commercial office building, both involved cast-in-place concrete construction techniques. Site C, a 10-floor hospital and surrounding facilities, involved tenant improvement activities. Due to a lack of available personnel at this site, additional monitoring was done at a fifth site, which was a similar tenant improvement project. The work and exposures at these two sites were very similar, allowing for aggregation, and are hereafter referred to as Site C. Sampling was conducted for 12 days at Sites B, C, and D, and 13 days at Site A. This methodology satisfied the recommended sampling guidelines of sampling over the course of a job and at different times during the job.(22–23)

One hundred thirty-three individuals volunteered to participate in the exposure assessment, 122 of which were employed by the general contractor participating in the study, and 11 of which were employed by various subcontractors. All workers employed by the general contractor at each site were given a brief presentation on the purpose and methods of the study; workers willing to participate were asked to sign an informed consent form. Full-shift noise dosimetry was done on as many as 10 workers (selected from a site's available pool of workers having signed informed consent forms) per monitoring day, depending on the number of workers and dosimeters available. This informal approach to enrolling workers does not allow for calculation of participation rates; however, the majority of workers approached were willing to participate. The data collection period of the exposure assessment lasted 22 weeks, with a total of 49 monitoring days occurring between July 2, 1997, and December 19, 1997.

Datalogging noise dosimeters were used to collect noise exposure data (five Quest Q-300 dosimeters, Quest Technologies, Oconomowoc, Wis.; five Metrosonics db-308, one Metrosonics db-3100, Metrosonics, Rochester, N.Y.). All instruments had similar manufacturers' specifications for microphone performance and data collection. Microphones were mounted on the shoulder of the monitored worker's dominant hand. All dosimeters were calibrated prior to and following each monitoring event; no postcalibration values were more than ±0.5 dB from the nominal calibration value for each model. Ambient conditions, including weather and temperature, never exceeded the operating range for any of the instruments used.

Two exposure metrics were utilized in this project: the U.S. Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL)(24) and the 1996 (draft) NIOSH proposed recommended exposure limit (REL)(25) (NIOSH published this document in final form in 1998;(10) unless otherwise specified, the NIOSH standard referred to in this article is the draft 1996 document.) The OSHA and NIOSH metrics share several parameters, including A-weighting and a 115 dBA maximum level(24,25) (the 1998 NIOSH document does away with ceiling limits). However, they differ in several key areas. The OSHA metric uses slow meter response, whereas the NIOSH metric allows for the use of either fast or slow meter response (dose calculation using a 3 dB ER is not influenced by response time (10,25,26)); OSHA sets



UW Construction Noise Study - Task Data Card **Trade: Ironworker**

Name (Please Print): **Date:** **Years in Trade:**

	AM						PM				
Activity	6	7	8	9	10	11	12	1	2	3	4
Bolt Up											
Weld and Burn											
Erect Iron											
Lay Metal deck											
Clean Up											
Break/Rest/Lunch											
Other:											

Tool Used	6	7	8	9	10	11	12	1	2	3	4
Hand Hammer											
Arc Cutter											
Grinder											
Impact Wrench											
Drill											
Seam Crimper											
Scaler											
Chop Saw											
Chipper											
Welding Torch											
Other											

FIGURE 1. Example of a trade-specific data card

an advisory ceiling level for impulse noise at 140 dB, whereas NIOSH sets none; OSHA uses an 80-dBA threshold (the level above which noise is integrated into dose), while NIOSH uses no threshold; and OSHA uses a 5-dB ER, whereas NIOSH and the International Organization for Standardization (ISO) recommend a 3-dB ER(27) based on the equal energy rule.(28) The less protective 5-dB ER allows for longer exposures at higher sound levels.

The data filtering and processing features of the three different types of instruments were very similar. Each dosimeter was programmed to record 1-min averages for the entire monitoring period, in addition to recording an 8-hour TWA and the average noise level for the duration of the sample period. Both models of Metrosonics dosimeters could collect only a single channel of data, whereas the Quest dosimeters could collect up to three channels of data, each according to a different exposure metric. One channel on all 11 dosimeters used in the study was set to collect according to the parameters set forth by OSHA, yielding 1-min L_{OSHA} averages and OSHA TWAs (90-dBA criterion, slow response, 5-dB ER, 80-dBA threshold). The second channel on the Quest dosimeters was set to measure noise according to the parameters promoted by NIOSH and ISO and yielded 1-min L_{EQ} averages and NIOSH/ISO TWAs (85-dBA criterion, slow response, 3-dB ER, no threshold).

Four trade-specific self-report data collection cards were used to track worker activities during the monitoring periods (an example is shown in Figure 1). These cards listed tasks and tools likely to be encountered by each trade and allowed the workers to report the times of day that tasks and tools were used with approximately 15-min time resolution. A card was distributed with every dosimeter each morning, and the completed cards were collected at the conclusion of each work shift. In addition to task and tool information, workers were asked to report their ages and years of experience in their current trades.

TWA and 1-min average data were assessed for normality using probability plots and histograms. The TWAs were approximately normally distributed; however, the 1-min average readings were truncated, resulting from the recording characteristics for values less than the threshold parameters of the Quest and Metrosonics dosimeters. Both models of Metrosonics dosimeters had operating ranges of 40–140 dBA, whereas the Quest dosimeters had an operating range of 70–140 dBA. The threshold setting in the OSHA exposure metric used in this study was 80 dBA; this meant that if no reading in any 1-min average exceeded 80 dBA, that 1-min average was assigned the instrument's lowest possible data value. The Quest dosimeters assigned 1-min averages with no readings exceeding 80 dBA the value of zero; however, the Metrosonics dosimeters assigned these readings the value of either 30.0 or 40.0 (the lower end of the two instruments' operating ranges). The data were modified to estimate these limit of detection readings. All 1-min averages below 43.5 dBA (the lowest valid reading in the Metrosonics data distribution) were recoded as missing, and then each missing value was replaced with an average of the first previous and subsequent nonmissing value. This data interpolation preserved the relationship between sequential minute averages, assigning values that were likely similar to the true values, and resulted in an approximately normal distribution of 1-min noise levels.

Data were downloaded into spreadsheet files for 1-min readings and TWAs separately. Task and tool use information was added directly to the 1-min sound level files according to time card recordings. Descriptive statistics were developed by trade, site, and stage of construction, and for the 1-min readings, by task and tool also. Several variables were simplified by grouping. Site was grouped by the construction method employed (cast-in-place concrete, tilt-up concrete, precast concrete, or tenant improvement). Task was grouped by the location on a site where a particular task might reasonably be expected to occur (interior of building, exterior of building, surrounding grounds, or other), and tools were

TABLE I. Subject Demographics and Number of Noise Measurements Made by Trade and Site

Trade	Parameter	Site A	Site B	Site C	Site D	Total
Carpenter	no. workers	27	9	10	11	57
	worker age (SD)	42 (9)	38 (11)	41 (6)	47 (9)	42 (9)
	years in trade (SD)	18 (5)	16 (8)	19 (6)	23 (8)	19 (7)
	no. of TWAs	44	26	29	23	122
	no. of L_{OSHA} mins[A]	21124	13057	14896	11344	60421
Laborer	no. workers	25	5	5	7	42
	worker age (SD)	40 (11)	39 (11)	40 (8)	44 (11)	41 (10)
	years in trade (SD)	14 (10)	14 (9)	13 (8)	15 (11)	14 (10)
	no. of TWAs	49	20	20	24	113
	no. of L_{OSHA} mins[A]	22931	10085	9575	11751	54342
Ironworker	no. workers	6	7	NA	6	19
	worker age (SD)	36 (7)	42 (5)	NA	47 (0)	41 (7)
	years in trade (SD)	12 (8)	16 (8)	NA	8 (6)	12 (8)
	no. of TWAs	14	19	NA	22	55
	no. of L_{OSHA} mins[A]	6712	9164	NA	9635	25511
Operating engineer	no. workers	1	7	NA	7	15
	worker age (SD)	55	48 (8)	NA	43 (12)	48 (8)
	years in trade (SD)	28	21 (11)	NA	19 (10)	21 (10)
	no. of TWAs	5	28	NA	15	48
	no. of L_{OSHA} mins[A]	1848	14273	NA	7467	23588
Total	no. workers	59	28	15	31	133
	worker age (SD)	41 (10)	42 (10)	41 (7)	45 (10)	42 (9.6)
	years in trade (SD)	16 (8)	17 (10)	17 (8)	16 (11)	16 (9)
	no. of TWAs	112	93	49	84	338
	no. of L_{OSHA} mins[A]	52615	46579	24471	40197	163862

[A] = minutes of monitoring performed using the OSHA noise level measurement parameters.

grouped by the basic drive mechanism employed (pneumatic, electric, gasoline, mechanical, or other). In addition, the stage of construction in which samples were taken was classified as either site preparation, structural work, or finish work.

Linear models were developed to summarize the TWA and 1-min averages separately. Potential predictors for the TWAs were trade, stage of construction, and construction method. Additional predictors for the 1-min averages were task location and tool drive. Models were selected based on least number of variables for highest R^2 and greatest significance. Additional models were run using indicators for individual tasks and tools in order to present the noise levels associated with this level of detail.

One-way random effects analysis of variance models with study subject as the effect variable were run to calculate the between- and within-subject variance components.(29) The between-subjects variance was used to estimate the probability of a worker's average exposure exceeding the criterion level. This exceedance probability (θ) was compared with the exceedance probability for individual measurements (γ).

To assess the accuracy of task/tool self-reporting, a researcher spent 8 randomly chosen monitoring days onsite (2 days per site), observing the workers and recording the activities and tools with which each monitored worker was involved. Crosstabulation tables were generated that compared worker-reported tasks and tools with researcher-observed tasks and tools; from this table, a Cohen's kappa statistic of agreement was calculated. The task-associated Cohen's kappa was 0.874 for the 5869 min in which there existed both observer and worker reporting; the tool-associated statistic was 0.829 for 1998 min of dual reporting (the number of minutes differs because tools are not used in all tasks). These statistics indicate excellent agreement between worker reporting and researcher observation.

RESULTS

A total of 370 samples were collected, including 16 on personnel in trades other than those targeted for the study and 16 involving instrument failures, leaving 338 valid samples on the 4 targeted trades. The 16 active instrument failures that occurred during datalogging represent a 4.3% failure rate for the total samples attempted. These instrument failures resulted from a number of causes, including excessive exposure to the elements, battery failure, and microphone lead failure.

Carpenters and laborers were well represented in the study, accounting for 36.1 and 33.4% of the valid samples obtained, respectively. Ironworkers and operating engineers were encountered less frequently and only at certain sites, and accounted for 16.3 and 14.2% of the valid samples, respectively. An attempt to oversample these trades was made once this deficiency was identified.

Workers in the four trades included in the study performed 39 unique tasks and used 32 different tools. In addition to tasks executed and tools used, workers reported their ages and years of experience. Worker demographic information, and the distribution of data collected by trade and site, are shown in Table I. Seven of the participating workers were monitored at two different work sites, and one worker was monitored at three different work sites. Repeated measures were taken on some workers at each site.

TWA results based on OSHA response definitions are presented in Table II. The mean duration for all monitored work shifts was 488 min (±67 minutes), with a range of 31 to 607 min, respectively (over 85% of valid TWAs were between 7 and 9 hours long). Forty-three OSHA TWAs of 338 (12.7%) exceeded the OSHA PEL of 90 dBA; 135 of 338 (39.9%) exceeded the OSHA action level of 85 dbA. In contrast, 82.0% of the 174 NIOSH/ISO TWAs exceeded 85 dBA, and 45.3% exceeded 90 dBA (Table III).

TABLE II. L_{OSHA} (5-dB ER) Noise Level TWAs

Variable	Categories	No. of TWAs	Mean (dBA)	SD	Min (dBA)	Max (dBA)	% > 85 dBA	% > 90 dBA	Avg. (SD) Minutes >115 dBA per TWA (Slow Response)	Avg. No. of Minutes with Peaks >140 dBA per TWA
Trade	carpenter	122	82.2	7.7	61.6	98.0	41.8	16.4	01:16 (04:41)	23
	laborer	113	83.3	7.1	64.8	99.3	41.6	13.3	03:32 (18:11)	15
	ironworker	55	82.3	5.9	69.8	95.2	30.9	9.1	07:40 (27:47)	25
	operating engineer	48	83.5	4.5	72.9	90.8	41.7	6.3	02:08 (05:27)	5
Site construction method^A	multiple concrete	112	86.3	5.2	73.7	99.2	63.4	21.4	02:22 (08:05)	18
	cast-in-place concrete	177	82.5	5.6	66.9	95.9	33.3	8.5	04:22 (20:50)	18
	tenant improvement	49	75.9	8.5	61.6	99.3	10.2	8.2	00:53 (02:06)	21
Stage of construction^A	site preparation	62	82.7	5.4	71.9	95.9	35.5	9.7	05:18 (23:33)	14
	structural work	193	84.3	5.8	66.9	99.2	47.7	15.5	03:21 (15:57)	19
	finish work	83	79.1	8.4	61.6	99.3	25.3	8.4	01:16 (03:41)	20
All samples		338	82.8	6.8	61.6	99.3	39.9	12.7	03:12 (15:49)	18

^{A}Difference between OSHA mean TWA levels in variable categories significant at $p < 0.001$.

OSHA TWAs did not differ significantly by trade (Table II). The type of construction associated with the highest OSHA TWA levels was multiple concrete construction methods, and the stage of construction associated with the highest OSHA TWA levels for all trades was structural work. The number of OSHA TWA exposures exceeding 85 and 90 dBA in all trades was found to be highest during the structural work stage of construction and at the site using multiple concrete construction techniques (Site A).

Table III describes the exposure data for the samples that include both an OSHA and NIOSH/ISO TWA. The 338 OSHA-based TWAs encountered in the study varied little by trade; the 174 NIOSH/ISO-based TWAs had more variability and were higher. The largest differences between OSHA and NIOSH/ISO TWAs occurred in the finish work stage of construction and at tenant improvement projects (NIOSH/ISO TWAs were 7.7 and 10.5% higher than OSHA TWA levels, respectively). Ironworkers and operating engineers, the multiple concrete and cast-in-place construction method sites, and the structural work stage of construction all had greater than 90% of NIOSH/ISO TWAs above 85 dBA. The differences between OSHA and NIOSH/ISO TWAs are due to the different exchange rates used in each metric: 5 dB for the L_{OSHA} readings that constitute each OSHA TWA, and 3 dB for the L_{eq} readings that constitute each NIOSH/ISO TWA. The range of the OSHA TWAs was 61.6–99.3 dBA, whereas the range of the NIOSH/ISO TWAs was 76.1–103.9 dBA.

Although no trade had a mean OSHA TWA level that exceeded the legally enforceable OSHA PEL, all trades had mean maximum levels and numbers of minutes with peaks above 140 dBA that exceeded the levels allowable for unprotected workers (Tables II and III). Ironworkers had the second-lowest OSHA TWA mean (only carpenters were lower), but had the highest mean number of minutes with peaks exceeding 140 dBA per TWA (28), and also had the highest mean time accumulated over 115 dBA (11 min 59 sec). This suggests that ironworkers generally are exposed to lower noise levels than operating engineers and laborers, but that these levels can be highly variable, and sometimes reach very elevated levels. Pneumatic tools and tasks involving the use of pneumatic tools were associated with the greatest L_{peak} and L_{max} exceedances. Peak and maximum readings can be generated artificially through microphone handling and microphone/object collision. The location of the microphone on the worker's lapel and the use of microphone covers should have minimized the occurrence of this sort of event; however, it remains possible that some of the peak data may have been contaminated by artificial events.

The linear model created using the TWA data explained almost

TABLE III. L_{OSHA} (5-dB ER) and L_{eq} (3-dB ER) Noise Level TWAs

Variable	Categories	No. of TWAs	Mean (SD) (dBA)		% >85 dBA		% >90 dBA		Avg. (SD) minutes >115 dBA per TWA (Slow Response)	Avg. (SD) minutes >115 dBA per TWA (Fast Response)
			L_{OSHA}	L_{eq}	L_{OSHA}	L_{eq}	L_{OSHA}	L_{eq}		
Trade	carpenter^A	53	80.3 (8.6)	88.5 (6.8)	35.8	67.9	13.2	49.1	02:47 (06:51)	04:21 (10:06)
	laborer^A	57	82.6 (7.5)	89.7 (6.4)	38.6	79.0	14.0	37.3	06:18 (25:20)	08:18 (30:11)
	ironworker^A	35	84.5 (5.2)	91.9 (5.2)	42.9	97.1	14.3	57.6	11:59 (34:16)	11:33 (34:55)
	operating engineer^A	29	84.0 (4.0)	89.3 (3.6)	44.8	93.1	10.3	34.2	03:32 (06:41)	02:48 (03:32)
Site construction method	multiple concrete^A	53	86.7 (4.8)	93.2 (5.0)	66.0	96.2	22.6	70.1	04:28 (11:19)	06:34 (20:00)
	cast-in-place concrete^A	85	83.2 (4.6)	89.6 (4.2)	35.3	91.8	8.2	41.9	08:49 (29:29)	09:15 (30:03)
	tenant improvement	36	74.9 (9.0)	84.8 (7.3)	11.1	36.1	11.1	14.4	01:11 (02:23)	01:21 (02:30)
Stage of construction	site preparation	40	82.4 (5.2)	89.0 (4.4)	27.5	87.5	12.5	38.7	08:11 (29:02)	09:11 (30:06)
	structural work^A	85	85.5 (4.4)	91.9 (4.8)	56.5	97.6	14.1	59.2	07:03 (23:33)	08:12 (27:07)
	finish work^A	49	77.5 (9.3)	86.6 (7.4)	20.4	49.0	12.2	24.7	02:05 (04:37)	02:28 (03:59)
All samples		174	82.5 (7.2)	89.7 (6.0)	39.7	82.0	13.2	45.3	05:54 (21:42)	06:48 (23:54)

^{A}Difference between mean L_{OSHA} and L_{eq} levels for variable categories significant at $p < 0.05$.

TABLE IV. Linear Regression Model Coefficients for TWAs (dBA)

Variable	Dummy Variables	β	Std Error	Significance
Background		76.21	1.309	0.000
Stage of construction	site preparation	3.96	1.528	0.010
	structural work	3.84	1.223	0.002
	finish work^A			
Trade	carpenter	−0.52	1.068	0.627
	ironworker	−1.99	1.182	0.093
	laborer	−0.09	1.077	0.930
	operating engineer^A			
Site construction methods	all concrete methods	7.88	1.320	0.000
	cast-in-place concrete	3.03	1.601	0.060
	interior finish^A			
	R^2	Significance		
Overall model	0.267	0.000		

^A Baseline level.

27% of the variance of TWA noise exposure, and was highly significant ($p<0.001$) (Table IV). Individual trades were not found to be significant when included in the model; however, trade was left in the model to enhance exposure prediction.

The 338 TWA samples collected represent 163,862 min of monitoring L_{OSHA} noise levels, with 87,976 corresponding minutes of NIOSH/ISO L_{eqs}. Of these 163,862 one-minute OSHA averages, 27.8% were greater than 85 dBA, and 12.9% were greater than 90 dBA. The *a priori* tool groupings used in the regression models were significant at the $p<0.05$ level, and this grouping strategy indicated that pneumatically driven tools had the highest mean value. Likewise, the *a priori* grouped tasks were significant at the $p<0.05$ level, and this grouping approach indicated that tasks likely to occur at the exterior of the structure under construction had the highest mean value. The individual tasks with the highest associated mean noise levels were associated with heavy equipment (i.e., backhoes and bulldozers) or pneumatic tools; likewise, the individual tools with the highest mean noise levels were pneumatic tools such as jackhammers and vehicles such as the roller compactor. Table V shows descriptive statistics for the 1-min averages by various categories.

The multiple linear regression model based on *a priori* task and tool groupings is shown in Table VI, and the model including parameters for individual tasks and tools is given in Table VII. The linear regression model created using the 1-min average time sequence data with *a priori* grouped tasks and tools was able to explain 13.9% of the variance in the averages, whereas the model using ungrouped (individual) tasks and tools explained 19.3% of the variability. Both models were highly significant ($p<0.001$).

The variance components of the TWA data were analyzed and are presented in Table VIII. Between- ($_{B}\sigma^2$) and within-worker ($_{W}\sigma^2$) variances are shown both as numeric values and percentage of total variance ($_{T}\sigma^2$) by trade and method of construction. Total variance varies considerably, with the multiple concrete construction methods having the smallest total variance and carpenters having the largest. Between- and within-worker variance are nearly equal percentages of total variance for ironworkers and operating engineers, whereas within-worker variance accounts for 99% of the

TABLE V. One-Minute L_{OSHA} Readings for Trade, Method of Construction, Stage of Construction, and *A Priori* Grouped Tasks and Tools

Variable	Grouped Categories	Count	Mean	Std. Dev.	Max	% > 85	% > 90
Trade	carpenter	60421	75.85	13.19	124.20	27.9	14.3
	laborer	54342	75.94	12.98	120.70	25.7	12.7
	ironworker	25511	76.02	12.58	121.60	25.6	12.0
	operating engineer	23588	78.83	11.02	117.30	34.6	10.4
Method of construction	multiple concrete	52615	79.60	12.32	124.20	37.3	19.2
	cast-in-place concrete	86776	76.52	12.19	121.20	26.9	11.0
	tenant improvement	24471	68.69	12.58	116.70	10.3	5.6
Stage of construction	site preparation	30963	76.21	12.36	117.50	26.1	10.9
	structural work	91930	78.51	12.14	124.20	33.3	15.5
	finish work	40969	71.57	13.15	117.30	16.5	8.4
Task location	surrounding grounds	23046	79.04	10.58	114.40	33.6	10.0
	interior of building	37902	72.39	12.75	117.90	17.1	8.3
	exterior of building	67457	79.05	11.81	124.20	34.7	16.4
	other	35457	73.64	14.12	121.60	22.2	12.8
Tool drive	electric	21514	75.99	12.29	124.20	26.2	10.7
	pneumatic	3841	86.14	15.13	117.50	56.5	43.5
	mechanical	11081	80.06	11.40	117.60	38.4	18.3
	gasoline	12716	80.81	10.58	117.90	41.1	13.5
	other	11471	75.22	12.81	121.60	35.8	18.2

TABLE VI. Linear Regression Model Coefficients for 1-Minute Average Time Sequence Data Using *A Priori* Grouped Tasks and Tools

Variable	Dummy Variables	β	Std Error	Significance
Background		67.51	0.167	0.000
Site construction methods	all concrete methods	5.44	0.129	0.000
	cast-in-place concrete	1.10	0.151	0.000
	interior finish[A]			
Stage of construction	site preparation	4.13	0.142	0.000
	structural work	5.08	0.114	0.000
	finish work[A]			
Tool drive mechanism	electric	−0.44	0.093	0.000
	gasoline	4.14	0.131	0.000
	mechanical	2.43	0.122	0.000
	pneumatic	11.44	0.202	0.000
	other drive[A]			
Task location	building interior	5.32	0.085	0.000
	building exterior	2.09	0.099	0.000
	surrounding grounds	4.36	0.143	0.000
	other location[A]			
Trade	carpenter	−0.28	0.138	0.040
	ironworker	−3.39	0.152	0.000
	laborer	−1.45	0.132	0.000
	operating engineer[A]			
	R^2	Significance		
Overall model	0.139	0.000		

[A]Baseline level.

total variance for the multiple concrete method of construction; between-worker variance never exceeds within-worker variance. The values γ (probability of individual measurements exceeding 85 dBA) are similar to θ (probability of worker means exceeding 85 dBA), indicating that, at least in the conditions represented by these data, individual measurement exceedance values are reasonable predictors of risk of overexposure.(30) This appears to be true even in situations such as the multiple concrete and tenant improvement projects in which the between-worker variance is a small portion of the total and exceedance values are small.

DISCUSSION

Although construction workers are known to be at increased risk of NIHL, there are few comprehensive data quantifying both average noise exposure levels experienced by the trades and identifying the noise sources responsible for those noise levels. By monitoring noise exposures in several trades and on several projects over time using datalogging noise dosimeters and activity/tool data cards, this study helps address these needs. The five loudest tools encountered, by mean level, were jackhammer, chipping gun, LeJeune gun, bulldozer, and rotohammer (96.3, 85.9, 85.7, 85.2, and 83.5 dBA, respectively), whereas the five loudest tasks were chipping concrete, doing dry pack work, operating a bulldozer, operating a manlift, and operating a backhoe (85.5, 85.2, 85.2, 82.7, and 82.6 dBA, respectively). Three of the five loudest tools were operated by laborers, whereas three of the five loudest tasks were performed by operating engineers. Despite the association of these particularly loud sources with individual trades, only small differences in average exposures were noted between trades, and these differences were not statistically significant, suggesting that general activities and tools in use in workers' surroundings are important predictors of exposure. On the other hand, stage and method of construction were important predictors of exposure, with building erection and multiple concrete construction methods being associated with the highest noise levels. The percentages of measurements and workers exceeding legal and voluntary criterion levels were similar, contrary to other research findings(30)—this is due to the normality of the noise data presented here. Between 30–40% of all measurements and workers in this study exceeded 85 dBA when categorized by trade. The overall percentage of workers exceeding 85 dBA in this study (40%) is larger than the NIOSH-estimated percentage of general building construction workers exposed to noise levels greater than 85 dBA (15.8%);(10) however, this study examined only four construction trades, whereas the NIOSH estimates are for all the trades involved in general building construction.

Care must be taken in interpreting the multiple linear regression models constructed in this study. The TWA model estimates the TWA likely to be encountered by a worker in a trade covered in the study working on a site involving one of the construction techniques included in the study. The 1-min time sequence models do not predict the TWA that would result from doing work with the tasks and tools listed, but rather the levels they would most likely encounter for the period of time spent working with those tasks and tools. These models cannot be directly used for compliance purposes; instead, they should be used to predict exposure levels for tasks and tools and to tailor control strategies. In addition, it is critical to account for all factors in the model to estimate a particular noise level. The coefficients within each categorical variable in the model indicate the relative contribution of different noise sources to the overall predicted noise level; therefore, these coefficients do not represent actual decibel measurements, but rather represent values that must be added to the baseline level to

TABLE VII. Linear Regression Model Coefficients for Noise Exposure Minute Readings Using All Tools and Tasks

Variable	Dummy Variables	β	SE	Sig
Background		65.81	0.219	0.000
Trade	carpenter	−2.01	0.192	0.000
	ironworker	−2.16	0.211	0.000
	laborer	−1.85	0.187	0.000
	operating engineer[A]			
Site construction methods	all concrete methods	4.06	0.147	0.000
	cast-in-place concrete	−0.13	0.170	0.458
	interior finish[A]			
Stage of construction	site preparation	4.08	0.148	0.000
	structural work	5.15	0.120	0.000
	finish work[A]			
Task	backhoe operation	10.62	0.495	0.000
	blowdown	4.95	0.562	0.000
	build forms general	9.53	0.165	0.000
	build gang forms	10.35	0.205	0.000
	chipping concrete	10.20	0.519	0.000
	cleanup	4.21	0.149	0.000
	crane operation	−0.47	0.440	0.282
	demolition	5.65	0.265	0.000
	dry pack	12.34	0.976	0.000
	erect iron	8.81	0.376	0.000
	excavate	12.41	0.669	0.000
	finish concrete	8.06	0.973	0.000
	forklift operation	8.10	0.286	0.000
	grade slab	9.36	0.471	0.000
	grouting	4.20	0.396	0.000
	hang plastic	7.02	0.357	0.000
	interior finish	3.28	0.192	0.000
	lay metal deck	7.79	0.338	0.000
	lay slick line	9.04	0.611	0.000
	layout	1.26	0.252	0.000
	materials acquisition	−0.50	0.380	0.189
	multiple tasks	10.68	0.194	0.000
	other task	4.60	0.184	0.000
	place rebar	9.02	0.247	0.000
	pour concrete	8.48	0.207	0.000
	pour watch	9.03	0.308	0.000
	rigging	6.42	0.277	0.000
	roller operation	1.17	1.494	0.433
	safety	6.63	0.367	0.000
	sanding	−4.39	1.493	0.003
	set columns	7.22	0.273	0.000
	strip forms	9.06	0.195	0.000
	supervising	3.41	0.326	0.000
	tie rebar	4.83	0.199	0.000
	weld 'n' burn	7.35	0.338	0.000
	wood framing	8.34	0.220	0.000
	work around carps	5.99	0.296	0.000
	break/lunch[A]			
Tool used	air compressor	9.78	0.399	0.000
	air hose	8.10	0.480	0.000
	backpack blower	−1.41	0.566	0.013
	bulldozer	15.44	0.549	0.000
	backhoe	1.61	0.494	0.001
	chipping gun	5.11	0.559	0.000
	compactor	3.35	0.727	0.000
	crane	3.36	0.443	0.000
	chop saw	0.28	0.354	0.424
	drill	3.13	0.353	0.000
	electric vibrator	1.00	0.307	0.001
	excavator	−3.03	0.765	0.000
	forklift	3.92	0.253	0.000
	grout machine	0.26	0.762	0.734
	grinder	8.07	0.876	0.000
	hand hammer	2.28	0.140	0.000
	hand power saw	1.62	0.194	0.000
	jackhammer	26.69	0.737	0.000
	LeJeune gun	4.22	0.544	0.000
	manlift	10.76	0.310	0.000
	multiple tools	1.89	0.109	0.000
	other hand power tool	−0.23	0.324	0.478
	powder actuated tool	2.65	0.879	0.003
	pliers	2.67	0.590	0.000
	roller compactor	10.35	2.098	0.000
	rotohammer	6.68	0.394	0.000
	screw gun	−1.35	0.230	0.000
	truck	−0.89	0.424	0.036
	table saw	4.88	0.781	0.000
	two-way radio	3.12	0.358	0.000
	vacuum	−1.83	0.366	0.000
	welding torch	−0.77	0.372	0.039
	none reported[A]			
	R^2	Sig		
Overall model	0.193	0.000		

[A] Baseline level.

predict a 1-min noise exposure level. For instance, to estimate the level associated with chipping concrete with a chipping gun, one must add the coefficients for task: chipping concrete (10.2) to those associated with tool: chipping gun (5.11), stage of construction (e.g., structural work, 5.15), construction method (e.g., all concrete methods, 4.06), and background (65.8) to obtain an estimated 90.3 dBA. Note that this is only an average level associated with this combination of task, location, tool, and so forth, and not the significantly higher level that might be experienced during the limited time actually spent operating the tool.

The linear models based on the 1-min data gathered suggest that the highest feasible 1-min exposure expected would be to a laborer working during the structural work stage on a site using multiple concrete construction methods and using a jackhammer to chip concrete: this theoretical exposure would yield a 111.91 dBA 1-min average. The linear model based on TWA data predicted the highest TWA exposure to be that of an operating engineer working on a site involving multiple concrete construction

TABLE VIII. Variance Components

Category	n	k	$_B\sigma^2$ (% of $_T\sigma^2$)	$_W\sigma^2$ (% of $_T\sigma^2$)	γ	θ
All samples	338	133	15.5 (35)	28.5 (65)	39.9	37.0
Carpenter	122	57	18.9 (36)	33.4 (64)	41.8	35.8
Laborer	113	42	12.9 (27)	35.7 (73)	41.6	41.3
Ironworker	55	19	18.6 (48)	20.1 (52)	30.9	36.3
Operating engineer	48	15	9.7 (49)	10.2 (51)	40.7	42.3
Multiple concrete	112	59	0.3 (1)	26.4 (99)	63.4	56.7
Cast-in-place concrete	177	59	15.9 (48)	17.4 (52)	33.3	37.3
Tenant improvement	49	15	6.3 (9)	65.8 (91)	10.2	11.9

Note: n = number of samples; k = number of workers sampled; $_B\sigma^2$ = variance between workers; $_W\sigma^2$ = variance within workers; $_T\sigma^2$ = total variance; γ = probability of measurements >85 dBA; θ = probability of worker means >85 dB.

methods during the structural work phase: the predicted TWA exposure is 87.93 dBA. The estimates from these two models are not inconsistent; a TWA can contain a number of extremely high 1-min averages and still remain below the criterion level. Laborers, for example, can be exposed to excessive noise levels by tools they use for relatively short periods throughout a work shift and yet still have lower TWAs than operating engineers who work on somewhat quieter heavy equipment continuously for an entire work shift.

The models created from the data and descriptive statistics indicate several areas of particular concern: these include exposures occurring during the structural work stage of a construction project, exposures occurring on a site using multiple concrete construction techniques, and the use of pneumatically driven tools. The high levels encountered during the use of pneumatic tools, and especially tools such as chipping guns and jackhammers, are of particular concern, and have also been identified in the literature as a major source of exposure.(8,13,17,18,31) It was estimated in 1980 that 52,626 construction workers were exposed to concrete breaking tools and 1,400,000 workers were exposed to pneumatic tools.(32) The existing literature also suggests that air compressors and heavy equipment are major noise sources;(8,13,17,18,31) the linear models created in this study confirm those findings. The study found interior finish work to be the quietest of the three construction methods examined; this agrees with previous research findings.(31) Earlier studies of heavy equipment suggest higher exposures in operating engineers than were found here(13,15,31)—however, many of these studies were based on SLM results, which are not directly comparable with the dosimetry in this study. Also, the population of operating engineers examined differed in these studies—the current study included tower crane operators, who are exposed to lower noise levels than their counterparts operating heavy equipment on the ground.

Large differences were noted between the TWAs obtained using 5- and 3-dB ERs, and the degree of difference is related to the degree of variability in noise within a day. Operating engineers, often assigned to operate a single vehicle for an entire work shift, had the smallest difference between 3- and 5-dB ER-based TWAs, whereas carpenters, ironworkers, and laborers, who had larger differences between TWAs based on the two ERs, were more likely to be exposed to highly variable noise levels. These findings are also supported in the literature. A 1996 study found that occupations exposed to variable noise levels had greater differences in TWAs based on 3- and 5-dB ERs than did occupations exposed to relatively constant noise levels,(33) and a recent study comparing TWAs generated by these two ERs in truck drivers following exposure to nearly constant noise sources (such as vehicle engine noise) found little difference between the two.(34)

Construction workers in all four trades included in this study were found to be exposed to impulse/impact noise, resulting in exposures above the OSHA-allowable maximum and peak levels. Impulse/impact noise may be a significant contributor to NIHL in the construction industry, as even the conservative 3-dB ER promoted in some noise exposure standards (and based on the physiologically derived equal energy rule) may not protect workers properly from hearing damage resulting from this type of noise.(35–37) Exposure to high levels of impulse noise may be more damaging to hearing than exposure to high levels of continuous noise(38) regardless of the ER used.

Hearing protection devices (HPDs) should be available to all construction workers, regardless of trade or site. However, engineering controls invariably provide better protection from overexposure and the resulting hearing loss: research indicates that construction industry HPD mean self-report usage rates range from 18–49% for carpenters and operating engineers exposed to noise within 3 months prior to being surveyed.(39) Regardless of the noise control approach used, workers must be trained properly in the use of HPDs, which are essential under some circumstances, and should receive audiometry annually and pre- and postemployment.

HPD usage data was not collected in this study despite the opportunity to do so via self-report and observation. This decision was made to avoid any potential negative impact on worker participation. HPDs were readily available at all sites included in the study and were used frequently, but not uniformly, by the monitored worker population. Due to the lack of HPD usage information, it is not possible to make direct dose and hearing loss predictions from the available exposure data; however, the data do indicate the potential for significant NIHL in unprotected workers.

Some of the findings of this study suggest effective control strategies. For instance, the mean of the 1-min average data associated with operating a bulldozer was 85.2 dBA, whereas the mean associated with operating a tracked excavator, a similarly sized piece of heavy equipment, was only 79.6 dBA. The operating engineers in both vehicles sit very close to engine and transmission components; however, the cab on the bulldozer is open on all sides, whereas the cab on the tracked excavator is enclosed by glass on three sides, effectively providing a noise transmission barrier. This barrier reduces noise levels below any existing noise exposure standard. Control strategies involving noise barriers, insulation, and equipment placement are appropriate for heavy and auxiliary equipment found on construction sites and are fairly well-described in the literature.(8,31,40–42) It was estimated in 1994 that a bulldozer operator's exposure could be reduced 11 dB for between $3,450–$4,300,(8) whereas the no-cost approach of situating an air compressor away from any vertical sound-reflecting surface can reduce the emitted noise level by 3 dB, and moving it away from a vertical corner can reduce the level by 6 dB.(41)

The trades and sites monitored in this study are reasonably representative of typical commercial building construction in the United States today. However, other construction projects, including roadwork, tunnel building, wood construction, and other types are not represented here, and tenant improvement projects are each unique; likewise, only a few of the building construction trades were included in this study. There is a subspecialty within the ironworker trade that deals solely with the erection of structural steel, but could not be included in this study due to a lack of workers willing to participate. There are indications that the noise levels encountered by these workers (who use more pneumatic and gasoline-powered tools than regular ironworkers) are higher than those encountered throughout the remainder of the trade, suggesting that the exposure levels estimated in this study are lower than actual values, and leaving a gap in the available data. Also, this study included operating engineers running tower cranes, a type of equipment not included in previous research. The very brief self-report data collection card used in this study did not allow for reporting of activities occurring in the monitored workers' surroundings; this information may be as critical to proper exposure modeling as recording what the worker was doing, given the relatively small amount of the variance in the data explained by the worker-specific data collected.

CONCLUSIONS

Construction workers routinely are exposed to noise levels exceeding allowable limits. No significant differences were found between the mean exposure levels for the four trades included in this study, suggesting that the general environment is an important predictor of individual exposure and risk; however, significant differences were identified between the different stages and methods of construction encountered. Heavy equipment and pneumatically driven tools contributed greatly to exposure levels. About 40% of the OSHA TWAs recorded exceeded 85 dBA, the level at which OSHA requires the implementation of a hearing conservation program; about 13% exceeded 90 dBA, the OSHA PEL. In contrast, over 80% of the NIOSH/ISO TWAs exceeded 85 dBA, and 45.3% exceeded 90 dBA. The mean level for OSHA TWAs was lower than the mean level for NIOSH/ISO TWAs, demonstrating the large effect of the ER on dose accumulation and TWA calculation for highly variable work such as that found in construction. The 80 dB OSHA threshold also may have contributed to the large difference between the two metrics; however, this contribution was probably small, given that 89% of all OSHA 1-min averages contained readings above 80 dBA. If the L_{EQ} metric were to be adopted, as has been recommended by most scientific bodies,(43) it would have significant implications for the construction industry.

The use of HPDs by construction workers was not assessed in this study and should be examined in future research. This study indicates that hearing conservation programs need to be implemented in construction workplaces, administered either by companies, labor unions, or independent organizations. Currently, most construction workers are not enrolled in effective hearing conservation programs due to the transient nature of their work locations. NIHL rates could be lowered through a broad-spectrum approach including an effective hearing conservation program, noise control engineering backed up by HPD use, and pre- and postemployment and annual audiometric testing. Depending solely on construction workers' use of HPDs is not a recommended approach in the worker population studied, as recent questionnaire-based research indicates usage rates are below 50%.(39)

This study suggests that workers in all four examined trades can be exposed at levels that exceed the allowable limits on any site during any stage of construction. However, the data indicate that overexposures are most likely to occur during the structural stage of construction work, at sites using multiple concrete construction techniques, and during the operation of heavy equipment and pneumatic tools. Therefore, focusing attention on these areas may result in exposure reductions, with a commensurate reduction of NIHL in construction workers and in the associated costs.

ACKNOWLEDGMENTS

The authors wish to thank Mark Hendricks and Dale Beam of Baugh Construction Co. for their support for this project, and the construction workers whose participation made this study possible.

REFERENCES

1. **Dobie, R:** Economic compensation for hearing loss. *Occup. Med. State Art Rev. 10*:663–668 (1995).
2. **Ringen, K.:** National Conference on Ergonomics, Safety, and Health in Construction summary report. *Am. J. Ind. Med. 25*:775–781 (1994).
3. **Kilburn, K.H., R.H. Warshaw, and B. Hanscom:** Are hearing loss and balance dysfunction linked in construction iron workers? *Br. J. Ind. Med. 49*:138–252 (1992).
4. **Ringen, K., and J. Seegal:** Safety and health in the construction industry. *Ann. Rev. Public Health 16*:165–188 (1995).
5. **Wu, T-N., S-J Liou, C-Y Shen, C-C Hsu, et al.:** Surveillance of noise-induced hearing loss in Taiwan, ROC: A report of the PRESS-NIHL results. *Prev. Med. 27*:65–69 (1998).
6. **Miyakita, T., and A. Ueda:** Estimates of workers with noise-induced hearing loss and population at risk. *J. Sound Vib. 205*:441–449 (1997).
7. **Arndt, V., D. Rothenbacher, H. Brenner, E. Fraisse, et al.:** Older workers in the construction industry: Results of a routine health examination and a five year follow up. *Occup. Env. Med. 53*:686–691 (1996).
8. **Schneider, S., E. Johanning, J-L Belard, and G. Engholm:** Noise, vibration, heat, and cold. *Occup. Med. State Art Rev. 10*:362–383 (1995).
9. **Welch, L., and P. Rota:** Medical surveillance programs for construction workers. *Occup. Med. State Art Rev. 10*:421–435 (1995).
10. **National Institute for Occupational Safety and Health (NIOSH):** *Criteria for a Recommended Standard: Occupational Noise Exposure* (DHHS [NIOSH] Pub. no. 98–126). Washington, DC: NIOSH, 1998.
11. **Behrens, V.J., and R.M. Brackbill:** Worker awareness of exposure: Industries and occupations with low awareness. *Am. J. Ind. Med. 23*: 695–701 (1993).
12. **McClymont, L., and D. Simpson:** Noise levels and exposure patterns to do-it yourself power tools. *J. Laryngol. Otol. 103*:1140–1141 (1989).
13. **Utley, W.A., and L.A. Miller**: Occupational noise exposure on construction sites. *Appl. Acoust. 18*:293–303 (1985).
14. **Kenney, G.D., and H.E. Ayer:** Noise exposure and hearing levels in the sheet metal construction trade. *Am. Ind. Hyg. Assoc. J. 36*:626–632 (1975).
15. **LaBenz, P., A. Cohen, and B. Pearson:** A noise and hearing survey of earth-moving equipment operators. *Am. Ind. Hyg. Assoc. J. 28*: 117–128 (1967).
16. **Pekkarinen, J.:** Noise, impulse noise, and other physical factors: combined effects on hearing. *Occup. Med. State Art Rev. 10*:545–559 (1995).
17. **Schneider, S., and P. Susie:** *Final Report: An Investigation of Health Hazards on a New Construction Project.* Washington, DC: Center to Protect Workers' Rights, 1993.
18. **Sinclair, J.D., and W.O. Haflidson:** Construction noise in Ontario. *Appl. Occup. Environ. Hyg. 10*:457–460 (1995).
19. **Shackleton, S., and M.D. Piney:** A comparison of two methods of measuring personal noise exposure. *Ann. Occup. Hyg. 28*:373–390 (1984).
20. **Hager, L.:** Sound exposure profiling: A noise monitoring alternative. *Am. Ind. Hyg. Assoc. J. 59*:414–418 (1998).
21. **American National Standards Institute (ANSI):** *American National Standard: Measurement of Occupational Noise Exposure* (ANSI S12.19–1996). Acoustical Society of America, 1996.
22. **Brunn, I.O., J.S. Campbell, and R.L. Hutzel:** Evaluation of occupational exposures: A proposed sampling method. *Am. Ind. Hyg. Assoc. J. 47*:229–235 (1986).
23. **Malchaire, J., and A. Piette:** A comprehensive strategy for the assessment of noise exposure and risk of hearing impairment. *Ann. Occup. Hyg. 41*:467–484 (1997).
24. "Occupational Noise Exposure: Hearing Conservation Amendment, Final Rule." *Federal Regulations 48*:9738–9785 (1983).
25. **National Institute for Occupational Safety and Health (NIOSH):** "Criteria for A Recommended Standard: Occupational Noise Exposure" (DHHS[NIOSH] draft document [96-XXX]). Washington, DC: NIOSH, 1996.
26. **American National Standards Institute (ANSI):** *American National Standard: Specification for Personal Noise Dosimeters* (ANSI S1.25–1991). New York: Acoustical Society of America, 1991.

27. **International Organization for Standardization (ISO):** *International Standard: Acoustics—Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment* [ISO 1999:1990 (E)]. Geneva: ISO, 1990.
28. **Burns, W., and D.W. Robinson:** *Hearing and Noise in Industry.* London: Her Majesty's Stationary Office, 1970.
29. **SPSS Inc.:** *SPSS Advanced Statistics 7.5.* Chicago: SPSS Inc., 1997. pp. 157–178.
30. **Boleij, J.S.M., E. Buringh, D. Heederik, and H. Kromhout:** *Occupational Hygiene of Chemical and Biological Agents.* Amsterdam: Elsevier Science B.V., 1995. pp. 97–136.
31. **Alfredson, R.J., and D.N. May:** Construction site noise. In *Handbook of Noise Assessment.* New York: Litton Educational Publishing, Inc., 1978. pp. 208–229.
32. **Poulos, A.C., D.E. Wasserman, and T.E. Doyle:** Occupational impact/impulse noise—an overview. *Sound Vib. 14*:8–12 (1980).
33. **Petrick, M.E., L.H. Royster, J.D. Royster, and P. Reist:** Comparison of daily noise exposures in one workplace based on noise criteria recommended by ACGIH and OSHA. *Am. Ind. Hyg. Assoc. J. 57*: 924–928 (1996).
34. **Seshagiri, B.:** Occupational noise exposure of operators of heavy trucks. *Am. Ind. Hyg. Assoc. J. 59*:205–213 (1998).
35. **Hamernik, R.P., and K.D. Hsueh:** Impulse noise: Some definitions, physical acoustics and other considerations. *J. Acoust. Soc. Am. 90*: 189–196 (1991).
36. **Levine, S., P. Hofstetter, X.Y. Zheng, and D. Henderson:** Duration and peak level as co-factors in hearing loss from exposure to impact noise. *Scan. Audiol. 27(suppl 48)*:27–36 (1998).
37. **Irle, H., J.M. Hesse, and H. Strasser:** Physiological cost of energy-equivalent noise exposures with a rating level of 85 dB(A): Hearing threshold shifts associated with energetically negligible continuous and impulse noise. *Int. J. Ind. Ergo. 21*:451–463 (1998).
38. **Mantysalo, S., and J. Vuori:** Effects of impulse noise and continuous steady state noise on hearing. *Br. J. Ind. Med. 41*:122–132 (1984).
39. **Lusk, S.L., D.L. Ronis, and M.M. Hogan:** Test of the health promotion model as a causal model of construction workers' use of hearing protection. *Res. Nurs. Health 20*:183–194 (1997).
40. **Kessler, F.:** Cost assessment of construction noise control. In *Noise and Vibration Measurement: Prediction and Mitigation,* Denver, May 1985. New York: American Society of Civil Engineers, 1985. pp. 33–43.
41. **Mulholland., K., and K. Attenborough:** *Noise Assessment And Control.* Essex, UK: Construction Press, 1981. pp. 74–76.
42. **Ottoboni, F., and T.H. Milby:** Occupational disease potentials in the heavy equipment operator. *Arch. Environ. Health 15*:317–321 (1967).
43. **Suter, A.H., and D.L. Johnson:** Progress in controlling occupational noise exposure. *Noise Control Eng. J. 44*:121–126 (1996).