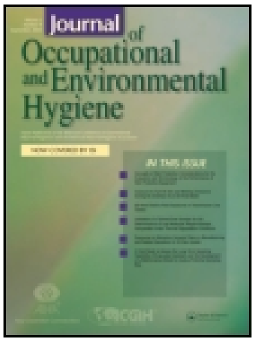

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The Effectiveness of Hearing Protection Among Construction Workers

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Effective hearing conservation programs in the construction industry are rare. Where programs are present, they often rely on workers' use of hearing protection devices (HPDs) rather than on exposure controls to reduce noise exposure levels. Dependence on HPDs for protection from high noise is problematic, as the protection provided by the HPD depends on both the HPD's attenuation level and the time the HPD is used. This article presents an analysis of data on noise exposure and hearing protection among construction workers drawn from several large datasets covering nine construction trades. A unique combination of 1-min dosimetry noise exposure levels and simultaneous self-reported use of HPDs was evaluated, as were occupational and nonoccupational HPD use data collected by questionnaire as part of a longitudinal study of noise exposure and hearing loss among apprentices. Direct measurements of HPD attenuation were also made on workers at their work site. The workers assessed in this study were found to use hearing protection less than one-quarter of the time that they were exposed above 85 dBA. Workers who reported "always" using HPDs in high noise on questionnaires were found to wear them only one-third of the time their exposures exceeded 85 dBA. Workers' self-reported use of HPDs during most noisy nonoccupational activities was also found to be low. Direct attenuation measurements found that workers were able to achieve more than 50% of the rated attenuation of their HPD on average, but that the variability in achieved attenuation was large. When the measured HPD attenuation levels and use time data were combined, the effective protection afforded by HPDs was less than 3 dB, a negligible amount given the high exposure levels associated with construction work. However, there was substantial variation in effective protection among the different trades assessed. These results demonstrate the need for better hearing conservation programs and expanded noise control efforts in the construction industry.

Keywords attenuation, construction, hearing conservation, hearing protection, noise exposure

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Exposure to high noise is common in the construction industry, and hearing loss is consequently prevalent in the building trades.[1] Although full-shift noise levels in the construction industry are high enough to warrant efforts at noise control,[2,3] hearing conservation programs in construction—where present—primarily depend on workers' use of hearing protection devices (HPDs). Unfortunately, workers' awareness of the risks of noise and other exposures is low in this industry.[4] and safety and health training is often lacking,[5] particularly in the case of hearing conservation programs, which are relatively rare in the industry.

Previous research has demonstrated that noise exposures to workers in a variety of construction sectors, trades, and operations frequently exceed a time-weighted average (TWA) of 85 dBA, the Recommended Exposure Limit of the National Institute for Occupational Safety and Health (NIOSH), and 90 dBA, the Permissible Exposure Limit of the Occupational Safety and Health Administration (OSHA).[2,3,6–10] Task- and tool-based exposure assessment techniques have also demonstrated high exposure levels during specific activities.[2,3,6]

Hearing loss, first reported in specific trades more than three decades ago,[11,12] continues to be prevalent throughout the construction industry.[6,13–15] The industry's primary reliance on HPDs, rather than noise controls, for exposure reduction places the burden of hearing conservation on exposed workers. Unfortunately, use of HPDs is poor among construction workers,[3,16–18] probably due to a combination of a lack of adequate worker education,[4] low availability of appropriate HPDs,[19] and perceived barriers to use.[20]

The amount of attenuation obtained from HPDs during high noise exposure is unclear. Dependence on the labeled attenuation rating on HPDs (in the United States, typically the noise reduction rating, or NRR) as a measure of individual attenuation is problematic,[21] as field studies on earplugs and earmuffs have consistently demonstrated that laboratory-derived measures such as the NRR bear little relation to attenuation achieved by workers in the field.[22–25] One alternative to using the NRR to estimate noise reduction is to make direct measurements on the attenuation achieved by individual workers. Systems designed for direct attenuation testing in field settings have been shown to perform adequately,[26] but field attenuation measurements often show large variability between individuals.[25] The variability in measured attenuation is due to a combination of factors, including user fit differences,[27] comfort and communications concerns,[28] and the amount of hearing conservation and HPD training received,[29] which is minimal for most construction workers.[18]

Even if direct attenuation measurement data are available, there is another, equally important factor that must be considered when estimating protection from noise exposure. Workers who do wear HPDs correctly, and achieve reasonable attenuation levels, but do not wear the HPDs for the majority of time they are exposed, experience greatly diminished effective protection as a result of exposure received during their nonuse time.[30] Noise-exposed workers, and particularly those in industries like construction where exposures are intermittent and exposure levels are highly variable, may not receive adequate effective protection due to low or irregular HPD use during high exposure periods.[16] Previous studies that have compared usage time to exposure levels have relied on worker self-report of perceived exposure level;[16,18] no previous studies have assessed HPD use in conjunction with simultaneously-monitored exposure levels.

The current study draws on a variety of noise exposure, HPD use, and HPD attenuation data collected on construction workers over a multiyear period and addresses several shortcomings in the existing literature on HPD use among construction workers. HPD use and time-matched, quantitative exposure data were collected on workers in nine different trades. Using these data together with mean real-world attenuation of HPDs measured on construction workers in the field, the effective protection achieved by a large cohort of workers was estimated.

METHODS

The data described here were collected from construction workers employed by a variety of contractors at many sites in the Puget Sound area of Washington state. All workers who participated in the various data collection efforts described below signed a University of Washington Institutional Review Board-approved informed consent form prior to participating in the research. Questionnaire data were derived from subjects participating in a five-year (1999–2004) longitudinal study of noise exposure and hearing loss among apprentice construction workers.[31] The cohort of construction workers enrolled in this study received a baseline and up to three annual follow-up questionnaires. Workers in the cohort worked in the following trades: carpenters, cement masons, electricians, heat/frost/asbestos insulation workers, ironworkers, masons, operating engineers, and sheet metal workers. Supplemental data described here were gathered from other construction workers in the same trades, as well as from laborers (who were not included in the longitudinal study) at participating worksites at various times between 1997 and 2004.

Noise Exposure Levels and HPD Use from Activity Cards

Simultaneous noise exposure and HPD use data were collected on workers over full workshifts. The noise exposure assessment techniques and exposure levels associated with these data have been described previously,[2,3,17] and were collected between October 1998 and March 2004. Briefly, workers wore datalogging dosimeters (Q-300; Quest Technologies, Oconomowoc, Wisc.), which logged exposure levels each minute of the monitored period. These dosimeters were configured to simultaneously measure the workers' exposure according to the several different exposure metrics. For this analysis, only the NIOSH REL was used; this standard specifies an 85 dBA criterion level, 3-dB exchange rate, slow response, and an 80-dBA threshold. While wearing the dosimeters, workers completed a trade-specific activity card describing their tasks, tools, environmental conditions, and HPD use throughout the entire workshift. Workers reported their activity timing and duration with an approximately 15-min time resolution using a preselected list of common trade-specific tasks and tools, or by reporting other specific tasks and tools not listed on the cards. Activity cards were completed during breaks and at the end of the workshift. A previous study[2] found that this reporting methodology yielded excellent agreement between worker-reported and researcher-observed task and tool use data.

These exposure and activity data were merged into a 1-min L_{eq} noise level/activity datafile for analysis. Arithmetic means and standard deviations of the percentage of total minutes in each workshift that exceeded 85 and 90 dBA were calculated, as were the percentage of minutes exceeding 85 and 90 dBA during which HPDs were used.

Occupational HPD Use from Annual Questionnaires and Activity Cards

Computer-based questionnaires that gathered information on subjects' demographics, medical history, construction employment history, occupational and nonoccupational noise exposure sources, HPD use, and other issues were delivered to all subjects participating in the longitudinal study. Specifically, workers were asked to report what percentage of time at each job (and the whole follow-up interval) was "noisy" (defined as noise levels high enough to require workers to raise their voice to communicate to someone an arm's length away), and how often HPDs were utilized during high noise exposure. HPD use was rated as "always," "sometimes," or "rarely or never." The percent of total responses that fell into the "always," "sometimes," and "rarely or never" categories were computed by follow-up interval and summarized for all responses and by trade.

For a subset of workers, the accuracy of self-reported questionnaire responses on HPD use was assessed by comparing dosimetry and activity card data with questionnaire responses.

Nonoccupational Use of HPDs from Questionnaires

In addition to questions regarding their occupational noise exposure and HPD use, the annual follow-up interval questionnaires contained questions about nonoccupational noise exposure, described in more detail elsewhere.[32] Subjects answering the questionnaire were also queried regarding their involvement in four noisy nonoccupational activities: use of firearms, attending loud recreational events, use of power tools, use of heavy equipment, and their use of HPDs during these activities.

Direct Measurements of HPD Attenuation on Construction Sites

The actual attenuation achieved by construction workers employed on six different sites operated by five contractors was quantitatively evaluated between November 2003 and April 2004 using a FitCheck attenuation measurement system (Michael and Associates, State College, Pa.). The same subjects also wore dosimeters and completed activity cards identical to the occupational noise exposure assessment methodology described above. Subjects were tested in a quiet area on site (in a work trailer, empty space, or in an automobile). The FitCheck system makes computer-controlled measurements (essentially Bekesy audiometry) of subjects' hearing thresholds in up to nine 1/3-octave noise bands, using loudspeakers mounted in circumaural earcups, under both occluded (HPD inserted) and unoccluded (no HPD inserted) conditions, and determines attenuation by calculating the difference between the two thresholds. Thresholds were tested at the following 1/3-octave frequency bands: 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 6300 Hz.

An overview of the general operation of the FitCheck system has been previously described elsewhere.[26] The FitCheck system was controlled using a Dell Inspiron 7500 laptop with an integrated Dell sound card running MS Windows 98. System output was checked daily by using a Quest Q-300 dosimeter set to measure real-time sound pressure level and placing the dosimeter microphone inside one FitCheck earcup. Six level reversals were required before a threshold at a specific frequency was accepted.

Subjects participating in attenuation measurements were brought to the test area at a convenient time during their workshift by the researcher. Subjects wearing earplugs at the time the researcher approached them for testing were instructed to leave their earplugs in; subjects not wearing earplugs were given a typical foam earplug (Howard Leight Max-Lite), and inserted the plugs prior to the test without any instruction or manipulation by the researcher. Each subject completed the attenuation test sequence once during a single workday. For most subjects, tests were performed in the following order: left ear, right ear, then binaural. In some cases, thresholds could not be measured for specific frequency bands because subject responses were too variable or the maximum output of the system was exceeded.

Frequency band-specific and overall attenuation levels (i.e., personal attenuation ratings, or PARs) were measured. The FitCheck system computed a PAR level automatically, following methods similar to an NRR calculation, immediately after the completion of the occluded and unoccluded tests. A 100 dB exposure is assumed in each 1/3-octave test band. Each band is then A-weighted, and the attenuation measured in each band by the FitCheck system is subtracted from these A-weighted levels. The log of the sum of the exponentiated occluded levels is then subtracted from the log of the sum of the exponentiated unoccluded levels, and the difference is the PAR level. This method differs from an NRR calculation in severals ways, including the frequency bands used in the calculation, the use of dBA instead of dBC levels, the lack of a 3-dB correction factor, and the lack of a standard deviation adjustment.

Since the test is delivered through earcups, it can only be used for earplug attenuation measurement. For purposes of comparing the measured PARs with the labeled NRRs, the NRRs were recalculated using the labeled attenuation for only the FitCheck frequency bands. The difference between the labeled NRR and the "adjusted" NRR was only 1 dB on average.

Mean adjusted NRRs and left and right ear and binaural PARs were computed for the groups of HPDs and overall, and frequency-specific arithmetic mean and standard deviation percentages of labeled attenuation achieved were also computed.

Adjustment of TWAs to Reflect HPD Use Time and Estimated Attenuation (Effective Protection)

TWA exposure levels were calculated from the 1-min intervals datalogged in each monitored workshift. Equation 1 was used to calculate these TWA levels.

$$TWA_i = 10\log_{10}\left[\frac{1}{480}\left(\sum_{k=1}^{n_i} 10^{Li/10}\right)\right] \tag{1}$$

where k is a 1-min interval within a workshift for individual i, L_i is the A-weighted L_{eq} average for a 1-min interval for the ith subject, and n_i is the number of 1-min intervals measured over the workshift.

To account for HPD usage time and HPD attenuation level, a protected NIOSH TWA was also computed using Equation 2.

$$TWA_{prot_i} = 10\log_{10}\left[\frac{1}{480}\left(\sum_{k=1}^{n_{ihp}} 10^{(L_i-H_a)/10} + \sum_{k=1}^{n_{inhp}} 10^{L_i/10}\right)\right] \tag{2}$$

where k is a 1-min interval within a workshift for individual i, L is the A-weighted L_{eq} average for a 1-min interval, n_{ihp} is the number of minutes in which HPDs were reported used, H_a is the mean HPD attenuation level measured on a group of workers, and n_{inhp} is the number of minutes in which HPD use was not reported.

Arithmetic means and standard deviations were calculated for individual TWA and TWA_{prot} data by trade and overall.

The difference between each individual's TWA and TWA_{prot} (in other words, the effective protection, P_{eff} provided by the HPD used over the course of a workshift) was then calculated, and means and standard deviations were computed on these differences.

RESULTS

Noise Exposure Levels and HPD Use from Activity Cards/Dosimetry

Full-shift noise dosimetry data and simultaneous activity card reporting of HPD use were collected on workers over 557 workshifts, representing nearly 275,000 min of exposure monitoring. These 557 shifts were gathered on 267 subjects, 138 of whom had only one measurement, and 129 who had, on average, 3.25 measurements each. The mean 1-min L_{eq} exposure levels, mean percentage of time that exposure levels exceeded L_{eq} levels of 85 and 90 dBA, as well as the mean percentage of time that HPDs were used when exposure levels exceeded these values, are presented in Table I. Mean 1-min exposure levels ranged from 77.9 ± 6.2 dBA for insulation workers to 84.6 ± 8.9 dBA for operating engineers; however, the range of levels for the remaining trades was much smaller, with six of the nine trades having mean levels between 80 and 82 dBA. Overall, exposure levels exceeded 85 dBA for nearly 30% of monitored minutes, but HPDs were only reported used 17% of these minutes. The percentage of time that HPDs were reported used when exposure levels exceeded 90 dBA is almost identical. Workers reported using HPDs 16% of the total time monitored, used earplugs 95% of the time that HPDs were worn, and earmuffs for the other 5% of time.

Operating engineers were the most noise-exposed trade, spending nearly half of their time above 85 dBA on average. Operating engineers also had the highest reported use of HPDs—nearly two-thirds of the time exposure levels exceeded 85 and 90 dBA. Conversely, ironworkers, the second most noise-exposed trade by mean percentage of time above 85 dBA, were among the trades that used HPDs least often—less than 10% of the time they were exposed above 85 and 90 dBA. Insulation workers and sheet metal workers were the trades with the lowest mean percentage of minutes above 85 dBA. However, while insulation workers had the lowest use of HPDs while exposed above 85 and 90 dBA, sheet metal workers had the second-highest use of HPDs during exposures above these levels. Electricians were exposed above 85 dBA more than one-quarter of the time but almost never used HPDs, even while exposed to high noise levels.

HPD Use from Annual Questionnaires

Annual questionnaires regarding employment in construction, noise exposure levels, and HPD use of the workers in the longitudinal study cohort were collected over annual follow-up intervals after the administration of the baseline questionnaire. Self-reported HPD use from 274 workers at follow-up interval one, 223 at follow-up two, and 165 at follow-up three (a total of 662 questionnaires) are shown in Table II. Overall, a little more than a tenth of workers reported wearing hearing protection "rarely or never," a little more than one-third reported wearing them "sometimes," and a little less than half reported wearing HPDs "always." The percentage of subjects in each category is fairly stable across follow-up intervals one to three.

Insulation workers and cement masons were the trades in which the highest percentage of workers indicated that they "rarely or never" used HPDs. Ironworkers, carpenters, and electricians were the trades in which the highest percentage of workers indicated that they "sometimes" used HPDs. Operating engineers, sheet metal workers, and masonry workers

TABLE I. Dosimetry/Activity Card Reported HPD Use >85 and 90 dBA

Trade	Number of Shifts	Number of Minutes	1-Minute Average L_{eq} Noise Level (dBA)		% Minutes in Shift >85 dBA		% Minutes >85 dBA HPD Used		% Minutes in Shift >90 dBA		% Minutes >90 dBA HPD Used	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Overall	557	274,468	81.0	8.0	28.7	19.2	17.1	34.9	12.8	13.1	17.5	35.6
Carpenters	81	39,027	81.7	8.0	33.0	14.1	22.0	37.2	16.1	10.2	22.0	36.9
Cement masons	31	14,764	80.8	7.8	26.3	18.4	16.7	31.5	11.4	9.8	19.2	35.4
Electricians	230	114,827	80.5	7.6	26.3	17.4	4.5	17.9	10.8	11.4	4.6	19.0
Insulation workers	23	11,597	77.9	6.2	15.0	17.5	4.3	20.7	4.5	5.9	4.5	21.3
Ironworkers	37	18,894	83.2	8.4	38.8	17.4	8.7	24.9	18.6	11.7	8.9	25.3
Laborers	6	2687	80.4	8.2	25.1	9.6	16.3	39.9	9.8	7.3	16.5	40.5
Masonry workers	73	34,437	80.5	8.9	25.5	18.5	25.3	40.5	13.3	13.4	26.5	41.4
Operating engineers	33	17,079	84.6	8.9	49.0	30.9	59.2	49.0	25.1	26.7	59.3	48.9
Sheet metal workers	43	21,156	80.6	6.4	24.0	15.2	43.3	46.8	7.0	6.2	43.1	47.1

TABLE II. Questionnaire HPD Use

Group	Number of Questionnaires	% Subjects Reporting HPD Use		
		"Always"	"Sometimes"	"Rarely or Never"
Overall	662	47.9	38.4	13.7
Year 1	274	45.6	39.1	15.3
Year 2	223	48.9	37.7	13.5
Year 3	165	50.3	38.2	11.5
Carpenters	148	42.6	42.6	14.9
Cement masons	62	22.6	41.9	35.5
Electricians	33	45.5	45.5	9.1
Insulation workers	36	47.2	30.6	22.2
Ironworkers	134	43.3	41.8	14.9
Masonry workers	155	56.8	36.1	7.1
Operating engineers	43	72.1	27.9	
Sheet metal workers	51	60.8	29.4	9.8

were the trades in which the highest percentage of workers indicated they "always" used HPDs.

Comparison of Annual Questionnaire Responses to HPD Use from Activity Cards and Dosimetry

HPD usage rates reported by workers in the longitudinal cohort on the annual follow-up questionnaires as "always," "sometimes," or "rarely or never" were compared with activity card and dosimetry data from monitored workshifts on the same group of workers. The results of this comparison for the 115 workers on which both questionnaire and activity card and dosimetry data were available are shown in Table III. The mean percentage of time that workers in all three HPD use groups were exposed above 85 dBA was very similar, roughly one-quarter of the time. Workers who reported "always" using HPDs had higher use times during exposures above 85 dBA (33% ± 43) than those reporting "sometimes" (13% ± 32) or "rarely or never" (0% ± 0) using HPDs. Self-reported HPD use varied widely by trade: for example, sheetmetal workers who reported "sometimes" using HPDs actually wore them 100% of the time above 85 dBA, while ironworkers and insulation workers who reported "always" using HPDs never wore them during exposure over 85 dBA.

Nonoccupational Use of HPDs from Questionnaires

The results of self-reported nonoccupational HPD use drawn from the questionnaire given to 289 subjects of the longitudinal study cohort at follow-up interval one are shown

TABLE III. Percentage of Exposure Time >85 dBA HPDs Used by Questionnaire-Reported HPD Use

Trade	Subjects Reporting HPD Use on Questionnaire[A]								
	"Always"			"Sometimes"			"Rarely or Never"		
	Number Subjects	Mean	SD	Number Subjects	Mean	SD	Number Subjects	Mean	SD
Overall	50	32.9	43.1	53	12.6	32.7	12	0	0
Overall % time >85 dBA	50	21.8	15.5	53	25.2	17.4	12	26.2	14.1
Carpenters	9	43.7	45.3	10	19.4	40.8	3	0	0
Cement masons	2	25.9	15.7	6	0.0	0			
Electricians	10	26.8	40.8	11	16.0	35.6	3	0	0
Insulation workers	4	0	0	4	0.0	0	2	0	0
Ironworkers	2	0	0	12	0.0	0	3	0	0
Masonry workers	13	28.1	44.2	8	12.5	35.4			
Sheet metal workers	10	56.9	49.2	2	100.0	0	1	0	

Note: n = 115 subjects who reported HPD use on activity cards.

TABLE IV. Nonoccupational HPD Use from First Follow-Up Questionnaire

Nonoccupational Activity	Subjects Reporting Activity	Self-Report HPD Use for Subjects Reporting Nonoccupational Activity		
	Number (%)	% Subjects "Always" Use HPDs	% Subjects "Sometimes" Use HPDs	% Subjects "Rarely or Never" Use HPDs
Firearms use	66 (22.8)	47.0	22.7	30.3
Loud recreation[A]	171 (59.2)	2.9	3.5	93.6
Power tool use	161 (55.7)	16.1	23.6	60.2
Loud machinery use	51 (17.6)	23.5	15.7	60.8

Note: n = 289 subjects.
[A]Concerts, dances, races, commercial sporting events, etc.

in Table IV. Four categories of nonoccupational activities are presented. Overall, self-reported nonoccupational HPD use was low; almost half the subjects who reported using firearms reported "always" using HPDs while shooting, but about one-third reported "rarely or never" using them. Nearly two-thirds of power tool users reported "rarely or never" using HPDs during this activity, and nearly all subjects who participated in loud recreational activities (attending concerts, dance, races, commercial sporting events, etc.) did not use HPDs during these activities. HPD use was also quite poor among subjects using loud machinery during nonoccupational time.

Direct Measurements of HPD Attenuation on Construction Sites

Table V shows the attenuation levels measured on a group of 44 construction workers from four trades (carpenter, cement mason, ironworker, and operating engineer). Although all workers recruited for this evaluation reported regular HPD use, 26 of the 44 workers were not wearing HPDs at the time they were approached to take a FitCheck test, and none of those workers had ever used HPDs at their current worksite. As a result, 26 attenuation measurements were made using the Howard Leight Max-Lite earplug provided at the time of the test. A total of seven different earplug models were tested (3M 1100, 3M 1270, DePlug 77200, E-A-R Classic, Howard Leight Max-Lite, Moldex Pura-Fit 6800, and Moldex Sparkplug). Since some models had only one or two attenuation measurements, they were grouped into three categories for comparison. The three groups consisted of the Howard Leight model (26 measurements), Moldex models (11 measurements), and all other models (7 measurements).

Workers achieved the highest mean binaural PARs using the Howard Leight plugs, which had the second-highest adjusted NRRs, and the lowest mean binaural PAR with the "other plugs," which also had the lowest adjusted NRR. The difference between the highest and lowest mean binaural PARs was very small (1.5 dB). Workers achieved more than 50% of the adjusted NRR on the earplugs tested for all three groups; however, the variability in attenuation achieved was quite high. The variation in attenuation achieved by workers across the four different trades was relatively small, with a range in the mean trade-specific PARs of a few dB.

Figure 1 shows the mean and SD binaural percentage of the labeled attenuation achieved at each of the frequencies tested for the three groups of earplugs. All three earplug groups achieved the highest percent of the labeled attenuation at 2000 Hz, and the lowest at 500 Hz. The amount of variability in the frequency-specific attenuation data was quite large, with standard deviations of the same magnitude as mean attenuation in some cases. Although there were small differences in

TABLE V. Measured Personal Attenuation Ratings (dB)

Type of HPD	Adjusted NRR (dB)	Left			Right			Binaural		
		Number of Tests	Mean	SD	Number of Tests	Mean	SD	Number of Tests	Mean	SD
Max-Lite	29	26	24.2	10.1	25	17.7	12.7	25	20.4	9.4
Moldex plugs[A]	31	11	22.4	12.0	9	25.6	8.8	9	17.6	9.1
Other plugs[B]	27.3	7	23.3	10.5	5	17.0	15.5	5	18.9	8.8
Overall	29.2	44	24.3	10.5	39	20.0	12.4	39	19.5	9.1

Note: n = 44 subjects.
[A]Moldex plugs: Pura-Fit 6800, SparkPlug.
[B]Other plugs: 3M 1100, 3M 1270, DePlug 77200, E-A-R Classic.

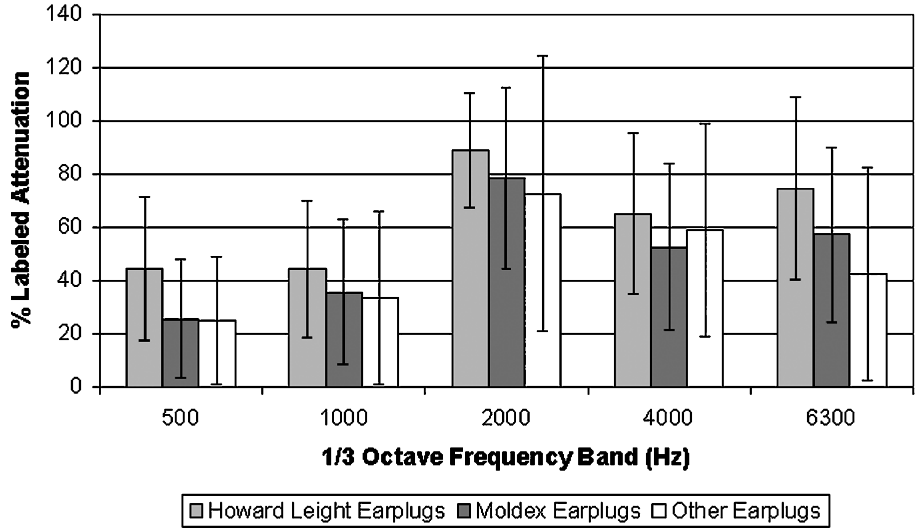

FIGURE 1. Percentage of frequency-specific labeled attenuation achieved

mean attenuation levels achieved at each frequency among the earplug groups, these levels did not differ significantly (t-test, $p > 0.05$).

Comparison of Unprotected and HPD-Adjusted Protected TWA Exposure Levels (Effective Protection)

The combined effects of HPD attenuation and use during exposure to noise levels above 85 dBA—in other words, the effective protection provided by the HPD—on the 557 full-shift TWA measurements for which 1-min data were available, are presented in Table VI. The unprotected overall NIOSH mean TWA was 87.4 dBA. The protected overall mean NIOSH TWA level, which reflects actual HPD usage time, and assumes an HPD attenuation of 20 dB (based on the direct attenuation results, Table V), was 2.7 dB lower than the measured exposure level. Nearly two-thirds of unprotected TWA measurements exceeded 85 dBA overall, and just over half of the protected TWA measurements exceeded 85 dBA; therefore, use of HPDs reduced overexposure situations by only about 20% overall.

Large differences in protected and unprotected exposure levels were seen between the trades. The largest mean difference (10.9 dBA) between protected and unprotected TWA levels was seen in operating engineers, who also had one of the highest unprotected TWA levels and percentage of unprotected TWA levels greater than 85 dBA. Conversely, ironworkers, who were even more highly exposed than operating engineers,

TABLE VI. Unprotected versus Protected[A] NIOSH TWA Exposures

Trade	Number Shifts	Unprotected NIOSH TWA (TWA, dBA)			Protected NIOSH TWA (TWA_{prot}, dBA)			Effective Protection, P_{eff} (Unprotected—Protected) (dBA)		
		Mean	SD	% >85 dBA	Mean	SD	% >85 dBA	Mean	SD	% Overexposures <85 dBA Due to HPDs
Overall	557	87.4	5.7	64.5	84.8	7.4	51.2	2.7	6.0	20.6
Carpenters	81	89.3	4.5	84.0	86.2	6.9	65.4	3.1	6.2	22.1
Cement masons	31	87.7	5.6	61.3	85.0	7.8	51.6	2.7	5.9	15.8
Electricians	230	86.7	5.5	59.1	86.2	6.2	56.1	0.5	2.5	5.1
Insulation workers	23	81.8	3.8	26.1	81.1	4.2	21.7	0.7	3.4	16.7
Ironworkers	37	90.7	5.5	83.8	89.5	6.3	78.4	1.2	4.1	6.5
Laborers	6	87.9	5.9	50.0	84.8	5.5	33.3	3.1	7.6	33.3
Masonry workers	73	88.5	6.7	65.8	84.4	7.0	43.8	4.1	7.0	33.3
Operating engineers	33	88.1	6.0	75.8	77.3	9.0	24.2	10.9	9.2	68.0
Sheet metal workers	43	85.7	4.2	53.5	78.8	8.0	25.6	6.8	8.4	52.2

[A] HPD-use adjusted.

had a much smaller (1.2 dBA) mean difference between protected and unprotected TWA levels. Sheet metal workers had low unprotected exposure levels and unprotected exceedance percentages, but had the second-largest difference (6.8 dBA) between unprotected and protected TWA levels. Finally, electricians had a fairly high unprotected TWA exposure level and exceedance percent, and yet had the lowest mean difference between protected and unprotected TWA levels.

The means and standard deviations of differences between protected and unprotected TWA levels for the different trades demonstrate the range of protection achieved by workers in these trades. Insulation workers, for example, have a very low mean difference between protected and unprotected TWAs and small standard deviation, indicating that few workers in this trade use HPDs regularly. Sheet metal workers, by comparison, have a higher mean unprotected-protected TWA difference, and a much larger standard deviation, indicating that workers in this trade use HPDs more often.

Five trades (operating engineers, insulation workers, laborers, masonry workers, and sheet metal workers) had mean protected exposure levels below 85 dBA; however, insulation workers had a mean exposure level below 85 dBA even without accounting for HPD use. Use of HPDs reduced overexposure situations among operating engineers by more than two-thirds, followed by sheet metal workers, with a reduction of more than half. Overexposure situations among electricians and ironworkers, however, were reduced by less than 7% by use of HPDs.

DISCUSSION

Evaluation of the effective level of protection that construction workers achieve when they use hearing protection devices is a critical step toward understanding and correcting shortcomings in noise exposure reduction efforts in this industry. The data analyzed here represent a unique opportunity to assess hearing protection use and effectiveness among construction workers in conjunction with information on their noise exposure levels. By combining information on usage time of HPDs and simultaneously-measured noise exposure data with direct measurements of HPD attenuation, this study has demonstrated that the protection afforded to construction workers by their hearing protection is small, and that they remain at high risk of hearing loss despite the industry's limited efforts at hearing conservation.

On average, the construction workers examined in this study reported using hearing protection less than one-quarter of the time that their measured exposure levels exceeded 85 dBA. Usage patterns varied among trades, with some trades wearing hearing protection often, while others almost never wore them. Operating engineers and ironworkers, for example, had similar exposure levels and exceedance percentages, yet operating engineers reported wearing hearing protection fairly regularly, and ironworkers rarely wore them. Further analysis of demographic factors on annual questionnaires indicated that females, nonwhites, and older (>30 years) workers were all slightly more likely to "always" wear hearing protection, but the difference between the groups was small (less than 10%). Interestingly, there was no apparent difference in HPD use based on audiometric results; 42–47% of subjects reported "always" using HPDs regardless of measured hearing ability.

Workers were far more likely to report hearing protection use during high noise exposure on annual questionnaires than on activity cards with simultaneous exposure measurement. Nearly half of workers reported "always" wearing HPDs when queried, in stark contrast to the time they were actually used when needed (around one-third of exposure time above 85 dBA). Subjects reported wearing HPDs far less during nonoccupational exposure than during occupational periods. Measured attenuation levels indicated that, on average, construction workers were able to achieve attenuation that was greater than half that of the labeled NRR but that variability between subjects was very large, such that some workers achieved more attenuation than the NRR, and some achieved almost none. Finally, when the measured average attenuation level was combined with use time, workers in most trades were found to have negligible effective protection, though the two trades with fairly high usage times gained enough protection to reduce their mean exposure levels to well below the NIOSH REL.

The noise exposure data gathered in the current study were measured using the NIOSH REL, which is more protective than the OSHA PEL (particularly under intermittent or variable noise exposure conditions) due to its lower exchange rate and criterion level. Previous research has shown that, while TWA exposure levels and exceedance percentages are higher using the NIOSH criteria, measurements made using the OSHA criteria still demonstrate substantial overexposures to noise.(2,3)

Previous studies on HPD use in construction have generally shown use to be low. Construction workers in five trades in British Columbia were found to use HPDs at a higher rate in 1997 than in 1988 following introduction of hearing conservation measures; however, another trade (laborers) showed no improvement despite these measures.(33) In another study, construction workers in three trades (operating engineers, carpenters, and plumbers/pipefitters) self-reported using hearing protection 18–49% of the time they were in high noise, despite a widespread knowledge of the effects of high noise exposure and acknowledgement that this exposure had already caused some hearing loss among the respondents.(16) As with the current study, operating engineers were found to have the highest use of HPDs, with far lower usage times reported by carpenters. The HPD usage rates of roughly 15% of work time previously reported on small subsets of the current dataset(3,17) remain consistent with the final results of this analysis, which includes a large quantity of additional data from other trades.

The questionnaire data reported here were derived solely from apprentices in the first 4 years of their apprenticeship programs. Apprentices may differ from construction workers, in general, in their self-protective behaviors. Given the increasing attention to safety and health in the industry, they might be expected to be somewhat more motivated to use personal protective equipment like HPDs than older workers. If so, the estimates presented here could be overestimates of HPD use in the industry in general. The dosimetry and activity card data were derived from a wider cross-section of commercial construction workers and may better reflect the industry average. No direct means for assessing the potential bias in our samples are available.

The low use of HPDs among construction workers is likely the result of a number of different factors. Lack of availability of HPDs on many construction sites is certainly a major factor. Reilly et al.[19] found that roughly 50% of inspected Michigan workplaces at which construction workers with an accepted hearing loss claim were employed did not regularly provide HPDs to workers on site. However, even when HPDs are available on construction sites, training on how to use them is often absent. In a survey of 50 construction workers with a mean seniority of 15 years, Dineen et al.[18] found that 86% had been supplied with HPDs by their employers, but only one-quarter had received training on HPD use. The workers demonstrated knowledge of the harmful effects of overexposure to noise and indicated that they had a high likelihood of developing hearing loss resulting from work in the industry, but the majority indicated that HPDs were only needed when noise was loud and constant and reported wearing HPDs less than 10% of time during the 3 months prior to the study.

Lusk and colleagues[20] have conducted several studies on HPD use and possible interventions. In a study of blue-collar workers based on application of the Health Promotion Model, four main barriers to HPD use were identified: self-efficacy (belief in one's ability to use HPDs correctly), perceived benefits of using HPDs, perceived value in using HPDs, and perceived barriers to using HPDs. Application of the same model to an HPD use training intervention targeted toward construction workers resulted in a significant increase in use of HPDs in some construction trade groups, but not in others,[34] demonstrating that training developed to address the needs and beliefs of a particular group of exposed workers can be effective.

In addition to adequate training materials, the HPDs available to workers must be appropriate for noise exposure levels, environmental conditions, and personal characteristics such as ear canal and head size. Overattenuation (wearing an HPD with more attenuation than is required for an individual's particular exposure) may be another reason construction workers do not wear HPDs as often as is needed. In variable noise exposure situations like those found in construction, workers may find that, during intermittent periods of quiet, HPDs prevent them from being able to communicate effectively. Also, the selection of hearing protectors available to workers can determine whether HPDs are worn or not; if only one protector is available (as is often the case on construction sites), and it has a very high degree of attenuation or is not very comfortable, workers are unlikely to use it, and will therefore have zero effective protection.

Studies that have compared attenuation achieved by workers in field situations with the rated attenuation measured in a controlled laboratory setting have repeatedly demonstrated that many workers achieve less than 50% of the rated attenuation, and that certain HPDs achieve only a few percent of the rated level.[22–25] The attenuation achieved by real-world HPD users is highly variable, and this variability prevents accurate prediction of real-world achieved attenuation from labeled ratings.[35] Previous research on HPD performance data has identified the distribution of attenuation levels measured in a group as typically bimodal,[27,36] with some workers achieving attenuation that approaches the labeled rating, and some achieving almost no reduction.

Workers in this study achieved an average attenuation of greater than 50% of the mean adjusted NRR, but the variability in attenuation achieved was large; as with previous studies, the distribution of attenuation was bimodal. Training on hearing conservation and the proper fit and use of the specific HPDs being used has been shown to be critical in achieving attenuation levels approaching the rated attenuation of that protector, and in reducing variability.[29,36]

The PAR attenuation observed in this study (mean level 20 dB) was also highly variable across the 44 subjects tested: the PAR standard deviation for all tests was 9–12 dB. This estimate of variability includes differences between subjects in the degree of HPD fit achieved, and also within-test variability in the test system itself. To address this uncertainty, a small test was conducted on 10 volunteers, each having two attenuation tests on a single type of earplug, separated by at least four hours and involving a refitting of the earplug. The results indicated the within-subject variability in PAR (calculated as the SD of the absolute difference in test PARs) was 4 dB in one ear, or 4.7 dB binaurally, and was higher than between-subject variability.

The FitCheck system used to measure attenuation in the current study, which is the only commercially available field-test system, has larger standard deviations than other systems used to measure attenuation via hearing thresholds.[26] While the within-subject variability seen in this substudy was high (frequency-specific SDs of 6–9 dB), the total variation in attenuation was still somewhat lower than in previous studies with the same test system (frequency-specific SDs of 7–12 dB,[25,26] and overall PAR SDs of around 11 dB.[36,37] The frequency-specific attenuation results of this study, which found that attenuation levels reached a maximum at 2000 Hz, are different from some previous studies, in which attenuation levels peaked at 4000 Hz or above.[22,23,25,26] The manufacturer of FitCheck is aware of this issue and is exploring the internal correction factors used by FitCheck to account for differences between attenuation measurements made using a sound field versus the TDH-39 headphones used for FitCheck testing as a possible explanation (personal communication with Kevin Michael, Michael and Associates, January 2005).

While occupational hearing conservation efforts are effective in controlling exposure to noise on the job, nonoccupational noise exposures are less easily reduced. Two recent articles by Neitzel et al.[32,38] have demonstrated that the majority of workers in the construction industry receive far less noise exposure off the job than on. Nevertheless, a small percentage of workers may have nonoccupational noise exposures high enough to contribute to hearing loss that might occur as a result of occupational exposure. Few studies have been conducted on use of hearing protection during noisy nonoccupational activities other than use of firearms, and those that have demonstrated low usage rates,[39] a finding consistent with the current study. HPD use during nonoccupational firearms exposures has been better documented; unfortunately, usage rates are still low, though they are far higher for target shooters than for hunters.[40] Shooters have been shown to wear HPDs more often during occupational exposure to noise than have nonshooters,[41] a finding not duplicated in this study. Roughly half of shooters in the current study reported "always" using HPDs while shooting, a level somewhat higher than those previously reported in the literature. Individuals who do use HPDs while shooting firearms can receive adequate protection from the impulse exposure they receive while firing;[42,43] however, those who do not use HPDs while firing undoubtedly add significantly to their risk of NIHL through this activity.

It would be useful to be able to predict worker's nonoccupational use of HPDs from their occupational use. To explore this relationship, the correlation between use of HPDs during occupational time and the four nonoccupational activities was computed, using categorical variables for the HPD use reporting categories ("always," "sometimes," "never"). These data are extremely sensitive to subject reporting bias, and the HPD use aspect of the questionnaire used to collect this data was not validated. However, the data available do indicate that the correlation between nonoccupational and occupational use of HPDs is generally low, with correlation coefficients ranging from 0.1 for HPD use while shooting firearms, to 0.5 for use while operating loud machinery off the job.

The effect of use time on the effective protection, P_{eff}, provided by an HPD, seen in Table VI, can be mathematically summarized with Equation 3, which is based on a 3-dB exchange rate.

$$P_{eff} = 10\log_{10}\left(\frac{100}{100 - p(1 - 10^{-N/10})}\right) \qquad \textbf{(3)}$$

where p = percentage of time the HPD was worn, and N is the nominal attenuation of the HPD.[28] Assuming a nominal attenuation of 20 dB, as was measured on the workers in this study, and an overall use rate of less than one-third of the time, the P_{eff} for the workers evaluated here is less than 3 dB, similar to what we found in our analysis.

If usage time were 100% for an HPD with an effective attenuation of 20 dBA, the difference between the protected and unprotected TWA levels would be 20 dBA. The much smaller difference between the protected and unprotected overall means (less than 3 dBA overall) demonstrates the effect of use time on effective protection. The mean difference between protected and unprotected TWA levels varies by an order of magnitude by trade (from 0.5 dBA for electricians to 10.9 dBA for operating engineers). This wide range of mean differences demonstrates that workers in some trades wear HPDs most of the time they are needed, and therefore achieve much more effective protection than workers in the same trade who have low usage time, even when all workers are assumed to have the same level of HPD attenuation.

All the previously presented results indicate the average HPD use for our cohort or subgroups of the dataset. Because personal protective equipment use depends substantially on individual motivation and behavioral factors, one would expect some individuals to be very well protected, and others very poorly. This possibility was explored by conducting a mixed effects analysis of variance to determine the degree to which variability in HPD use was associated with individual differences or variability in reported use from day to day within individuals, after controlling for the substantial differences observed in HPD use by different trades. As expected, two-thirds of the variability was associated with interindividual differences, with only one-third of the variability in reported use from day to day. While this analysis demonstrates significant between-individual variability in HPD use, there was an insufficient quantity of repeated measurements on each subject to allow a detailed analysis of individual HPD use patterns or to stratify the analysis by other factors that could explain differences in HPD use.

Much of the reported HPD use information described here came from the longitudinal study cohort; however, the noise exposure and attenuation level data were drawn from workers outside the cohort. These data sources were combined to allow for estimates of HPD use and effective protection from noise exposure. Although there is no reason to believe that any of the different groups of workers evaluated differed significantly in HPD use or attenuation, it is possible that some systematic bias was introduced as a result of the data combination.

Attenuation measurements can be made only on earplugs due to FitCheck system limitations, and therefore no attenuation estimates could be provided for earmuffs. However, as earmuff use was rarely reported by the subjects assessed, the attenuation estimates provided here should be generalizeable to the majority of construction work. Also, many of the subjects on which direct attenuation measurements were made used an earplug provided by the researcher, rather than their usual HPD; this could mean that the measured attenuation levels presented here underestimate the actual attenuation achieved by workers with their normal HPD. Application of the mean attenuation level measured on a small group of workers to a much larger set of full-shift exposure levels is a simplistic approach to exposure modeling and obviously does not account for individual differences in HPD attenuation.

For an individual in a given trade, the mean effective protection is not overly meaningful. However, taken across all subjects tested in that trade, the effective protection should be representative. Although self-reported work history data has been shown to have reasonable accuracy,[44] and the work history aspect of the questionnaire used in this study has been validated,[17] the HPD use aspect of the questionnaire in this study was not validated. Lusk et al.[45] found that self-reported use of hearing protection among 48 blue-collar workers, on average, differed little from observed HPD use and was far more accurate than supervisor reports of worker use, though workers tended to overreport their HPD use slightly overall. In contrast, comparison of the questionnaire and activity card data in the current study showed a significant overreporting of HPDs, with those reporting "always" using HPDs actually wearing them only about one-third of the time they were exposed above 85 dBA based on activity card and dosimetry analysis. The self-report questionnaire data in this study were therefore vulnerable to subject reporting bias.

One reason for this difference in findings is that the workers studied by Lusk et al. worked in a manufacturing facility with highly predictable noise levels and therefore had much more consistent and easily-summarized patterns of HPD use than do construction workers, who are exposed to highly variable and unpredictable noise levels. The 1-min noise exposure and HPD use data from which the effective protection levels were calculated were collected using a method that has been validated and are therefore much more reliable.

CONCLUSIONS

The analysis presented here of HPD use in a large dataset of workers demonstrates the inadequacy of HPDs alone for reducing occupational noise exposures in the construction industry. When hearing protection use and real-world HPD attenuation were considered, the effective protection achieved among all the construction workers evaluated was less than 3 dBA, and only about 20% of overexposure situations were reduced to levels below 85 dBA through the use of HPDs.

Clearly, additional efforts, including expanded availability of hearing protection and training on how, when, and where hearing protectors are to be worn, are needed. However, even with educational efforts, construction workers may not regularly use HPDs. Dineen et al.[18] found that even after completing hearing conservation education programs, 25% of construction workers still reported not using HPDs, a finding consistent with Lusk's previous studies demonstrating the difficulty in changing construction workers' future intention to wear HPDs. These studies, and the current results, suggest that reliance on hearing protectors alone to reduce noise exposure among construction workers is a flawed strategy and emphasize the need for concerted efforts towards the development of effective and simple noise controls for the construction industry.

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