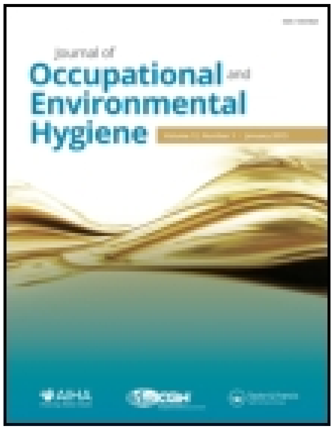

Journal of Occupational and Environmental Hygiene

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uoeh20

Effectiveness Evaluation of Existing Noise Controls in a Deep Shaft Underground Mine

Eric A. Lutz[a], Rustin J. Reed[a], Dylan Turner[a], Sally R. Littau[a], Vivien Lee[a] & Chengcheng Hu[b]

[a] Mining Safety and Health Program, Environmental and Occupational Health, Division of Community, Environment, and Policy, Mel & Enid Zuckerman College of Public Health, University of Arizona, Tucson, Arizona

[b] Department of Biostatistics, Division of Epidemiology and Biostatistics, Mel & Enid Zuckerman College of Public Health, University of Arizona, Tucson, Arizona

Published online: 01 Apr 2015.

To cite this article: Eric A. Lutz, Rustin J. Reed, Dylan Turner, Sally R. Littau, Vivien Lee & Chengcheng Hu (2015) Effectiveness Evaluation of Existing Noise Controls in a Deep Shaft Underground Mine, Journal of Occupational and Environmental Hygiene, 12:5, 287-293, DOI: 10.1080/15459624.2014.987385

To link to this article: http://dx.doi.org/10.1080/15459624.2014.987385

Journal of Occupational and Environmental Hygiene, 12: 287–293
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459624.2014.987385

Effectiveness Evaluation of Existing Noise Controls in a Deep Shaft Underground Mine

Eric A. Lutz,[1] Rustin J. Reed,[1] Dylan Turner,[1] Sally R. Littau,[1] Vivien Lee,[1] and Chengcheng Hu[2]

[1]Mining Safety and Health Program, Environmental and Occupational Health, Division of Community, Environment, and Policy, Mel & Enid Zuckerman College of Public Health, University of Arizona, Tucson, Arizona
[2]Department of Biostatistics, Division of Epidemiology and Biostatistics, Mel & Enid Zuckerman College of Public Health, University of Arizona, Tucson, Arizona

Noise exposures and hearing loss in the mining industry continue to be a major problem, despite advances in noise control technologies. This study evaluated the effectiveness of engineering, administrative, and personal noise controls using both traditional and in-ear dosimetry by job task, work shift, and five types of earplug. The noise exposures of 22 miners performing deep shaft-sinking tasks were evaluated during 56 rotating shifts in an underground mine. Miners were earplug-insertion trained, earplug fit-tested, and monitored utilizing traditional and in-ear dosimetry. The mean TWA_8 noise exposure via traditional dosimetry was 90.1 ± 8.2 dBA, while the mean in-ear TWA_8 was 79.6 ± 13.8 dBA. The latter was significantly lower ($p < 0.05$) than the Mine Safety and Health Administration (MSHA) personal exposure limit (PEL) of 90 dBA. Dosimetry mean TWA_8 noise exposures for bench blowing (103.5 ± 0.9 dBA), jumbo drill operation (103.0 ± 0.8 dBA), and mucking tasks (99.6 ± 4.7 dBA) were significantly higher ($p < 0.05$) than other tasks. For bench blowing, cable pulling, grinding, and jumbo drill operation tasks, the mean in-ear TWA_8 was greater than 85 dBA. Those working swing shift had a significantly higher ($p < 0.001$) mean TWA_8 noise exposure (95.4 ± 7.3 dBA) than those working day shift. For percent difference between traditional vs. in-ear dosimetry, there was no significant difference among types of earplug used. Reflective of occupational hearing loss rate trends across the mining industry, this study found that, despite existing engineering and administrative controls, noise exposure levels exceeded regulatory limits, while the addition of personal hearing protection limited excessive exposures.

Keywords mining, noise, noise controls, noise exposures, underground mining

Address correspondence to: Eric A. Lutz, Director, Mining Safety and Health Program, Mel & Enid Zuckerman College of Public Health, University of Arizona, 1656 E. Mabel St., #113, Tucson, AZ 85724; e-mail: ealutz@email.arizona.edu

INTRODUCTION

Noise continues to be a prevalent problem in underground mining, and poses a threat to miner safety and health.(1–3) Occupational exposure to noise not only damages hearing, but has been shown to negatively affect acute and chronic measures of cardiovascular health,(4–10) and increase risks of workplace accidents and injuries.(11–14) Despite these dangers, only a small number of English-language studies of noise exposure and controls in mining have been published in the last two decades.(1)

Though some progress has been made in reducing noise exposure levels, the prevalence of U.S. miners indicating they encounter hazardous noise in the workplace (77.2%) is second only to employees in the vehicle manufacture and repair industry (82.3%).(15) One study, utilizing survey data, estimated that the prevalence of hearing difficulty within the U.S. mining industry (24.3%) was second only to railroad workers.(16) In addition, the prevalence of noise-induced hearing loss (NIHL) among miners is greater (27.0%) than any other industry.(17) The challenge of reducing hazardous noise levels in the underground mining sector is impacted by the inherent nature of the work (i.e., the continuous use of heavy equipment, mechanically breaking rock formations, and the enclosed work environment), and underscores the need for comprehensive evaluation of the effectiveness of proposed and in-place noise control interventions.

The Mine Safety and Health Administration's(MSHA) permissible exposure limit (PEL) prohibits personal, outer-ear, 8-hour time-weighted average (TWA) noise exposures above 90 dBA or noise doses above 100%. In calculating noise exposure dosage and TWA, instruments using MSHA weighting utilize an exchange rate of 5 dB. In addition, all miners whose TWA exposures exceed 85 dBA must be enrolled in a hearing conservation program (HCP). In contrast, the American Conference of Governmental Industrial Hygienists (ACIGH®) threshold limit value (TLV®) recommends limiting TWA noise exposures to less than 85 dBA, a level at which the National Institute for Occupational Safety and Health (NIOSH) suggests the excess risk of material hearing impairment is acceptable.[18]

While innovations in noise control technology have been steadily introduced into the mining sector over the past decade, protection devices (HPD) (i.e., personal hearing protection equipment) are popular workplace noise controls due to their relatively low cost, ease of implementation, and common availability. However, this has led to sole- or at least over-reliance on them as a noise control. Effective attenuation from HPDs depends on the selection of quality devices, as well as the proper training of, consistent use by, and adequate fit in each miner. Unfortunately, the estimated weighted proportion of U.S. miners not using HPDs is 12.9%,[15] while 48% of American miners reported never using HPDs in one study.[19] The observed usage rate of HPDs by South African miners in another study was similar, at 50%.[20] Considering the high prevalence of hearing loss in the mining sector, there is considerable value in developing a systematic approach for evaluating the true effectiveness of HPD and combined noise controls.

Metal and non-metal mining technology is rapidly developing to access large bodies of bulk ore in harder to reach, deeper deposits. Block cave mining, an efficient technique that uses gravity to extract the ore, is increasingly proposed in these situations. Deep shaft sinking is integral to reaching these deep ore deposits and mine operators and industry leaders are seeking innovative solutions to control noise exposures presented by this unique mining application. Shaft sinking involves drilling, blasting, shotcreting, and mucking (debris removal) activities that produce significant noise exposures to personnel within the shaft. Regarding noise exposures, the shaft serves as a resonating chamber reverberating sound pressure levels at the work zone with little dampening and few options for engineering controls.

Traditional evaluation of effectiveness for proposed, or in-place, noise control interventions is accomplished using shoulder-placed noise dosimeters (traditional dosimetry) coupled with an instantaneous noise survey (including octave band analysis) and a time-motion study. While this study included these components, our novel research utilized methods to measure the actual sound pressure level inside the ear canal (behind the hearing protector) with existing engineering controls, administrative controls, and personal protective equipment in place using a prototype version of the Sperian Hearing Protection, LLC QuietDose (now Howard Leight by Honeywell, Smithfield, RI). In this study, we hypothesized that personal controls would prove sufficient in protecting miners' hearing, and that all controls combined (HPD and existing administrative and engineering controls) would attenuate sound pressure levels to below the MSHA PEL. We also hypothesized that noise TWA_8 exposures would vary by task, shift, and type of earplug, and that traditional and in-ear dosimeters measures would positively correlate.

METHODS

Participants

At a deep shaft underground metal mine in the United States, 22 miners were recruited on a voluntary basis and followed during a 2-week period, working a total of 56 distinct shifts on a rotating schedule. Shift worked included day (0800–1600 hours), swing (1600–2400 hours), and night (0000–0800 hours) in two different shafts (#9 and #10). Each worker's noise exposures were monitored during an average of approximately 2.5 shifts. Workers chose one of five types of Sperian Hearing Protection, LLC earplugs most similar to the HPD they typically wore. These QuietDose earplugs, with respective material and noise reduction rating (NRR), included: Acusonix (foam material, 30), Fusion LG (large size, flanged plastic-rubber material, 25), Fusion S (small size, flanged plastic-rubber material, 25), Matrix (TPE foam material, 29), and Smartfit (TPE molded plastic material with metal inserts, 25). To ensure study participants were properly using their chosen Sperian hearing protection, each was evaluated for pre-training hearing protection donning performance, trained in hearing protector use, and fit-tested using the Sperian Hearing Protection, LLC VeriPRO system (Honeywell International, Inc., Morristown, NJ). Prior to the initiation of the study, participant and data-related research methodology was reviewed and approved by the University of Arizona Institutional Review Board (IRB).

Data Collection

A prototype version of the Howard Leight QuietDose technology (Honeywell International, Inc, Morristown, NJ) was utilized to capture in-ear, data-logged sound pressure levels (SPLs) and full-shift integrated measurements behind the hearing protector (in-ear dosimetry). This system utilized Sperian earplugs with microphone-in-real-ear (MIRE) technology, with the microphone set inside a small hole that traveled through the center of the earplug. Traditional noise dosimetry was completed with 3M EDGE eg5 noise dosimeters (3M Company, St. Paul, MN). Both dosimeter models collected noise dosage data using the Occupational Safety and Health Administration's (OSHA) and American Conference of Governmental Industrial Hygienists' (ACGIH) weighting and exchange rates (5dB for OSHA, and 3dB for ACGIH). The weighting utilized by MSHA is identical to that of OSHA. All dosimeters were calibrated with the manufacturer-provided calibration device before each shift.

After the work shift, dosimeters were collected and a basic job task questionnaire, developed specifically for the study, was administered. The job task portion of the questionnaire was a simple written survey asking workers to recall the tasks they had performed during their shift. Specific data regarding the percent of time workers wore their HPD, and the sequencing, duration, and time-overlap of job tasks were not collected. Active shaft mining job tasks, such as drilling (simultaneous compressed-air driven drills with mufflers driving four, 32-millimeter steel bits), mucking (simultaneous mucking using two pneumatic clam-scoops), shotcreting (concrete gunite application activities), blowing bench (cleaning the bench with a compressed air hose), and loci operation (locomotive transport of muck) were particularly targeted.

Statistical Analysis

Each subject's whole-shift noise TWA_8 exposures were assigned to all tasks performed and the HPD type utilized by the individual (i.e., on a given shift, the noise exposure for each task performed by the individual was identical to that miner's exposure for the entire workday). The QuietDose prototype dosimeters do not provide a data-logged time series, nor do they calculate the TWA_8 noise exposure; OSHA and ACGIH TWA_8 exposures were manually calculated afterwards using the following equations:

$$\mathrm{TWA} = 16.61\log(10)\,(\mathrm{D}/100) + 90 \quad \textbf{(1)}$$

and

$$\mathrm{TWA} = 10.0 \times \log(\mathrm{D}/100) + 85 \quad \textbf{(2)}$$

respectively. Before comparing manufacturer NRR to observed differences from traditional to in-ear TWA, an adjusted NRR was calculated by subtracting seven from the original NRR and applying a 50% correction factor, per the OSHA recommendations. Investigators were not permitted to accompany miners underground and, unfortunately, there were instances in which researchers suspected, and data analysis confirmed, that some miners were not properly wearing their HPDs. Data for nine (out of 25) in-ear dosimetry measurements were removed because in-ear dosimetry measures were greater than traditional dosimetry on the same individual. Further, due to extremely small sample sizes, median differences in TWA_8 for Fusion LG, Matrix, and Smartfit earplugs were not compared to their adjusted NRRs.

All statistical analysis was performed using STATA version 12 (StataCorp, LP, College Station, TX). Due to small subgroup sizes and mostly non-parametric sample distributions, mean comparisons were performed using the Wilcoxon rank-sum test and Kruskal-Wallis rank test with Bonferroni corrections. The Chi-square test was used to measure shift and job task sub-group differences. The time-weighted noise reduction was also studied, which was calculated as the TWA dosimeter measure minus the TWA in-ear measure.

For correlation and regression, the TWA noise levels and peak noise levels were first examined graphically and peak noise levels were log transformed to achieve approximate normality. For each of the TWA_8 and log peak noise levels, the relationship between traditional dosimeter and in-ear dosimeter measurements were first studied by the Pearson's correlation coefficient and the nonparametric Spearman's rank correlation. Linear regression models were then used to further study the relationship among different noise measures and other characteristics, including shift and location. Multiple-covariate models were also fitted to study each of the four noise measurements (traditional and in-ear TWA_8 and log peak). A backward elimination process was employed, starting with the full set of covariates, including shift and location. The covariate "shift" had three levels and the overall p-value was obtained using an F-test, while p-values of all other covariates were obtained using the t-test. For all analyses, an alpha error threshold of 0.05 was applied.

RESULTS

The average sampling time was 509 (±22) minutes. Job tasks were classified into 23 separate task types, including: air impact (drilling), air pulley, backhoe operation, blowing bench, cable pulling (electrical), chipping, electrical tools, fork lift operation, grinding, hoisting, jackleg drilling, galloway operation, jumbo drill operation, loading, tug maintenance, loci operation, mucking, plasma cutting, pumping water, support services (labor), shop work (maintenance and supervision), surface support, tram-muck, and welding. Each worker performed an average of two tasks per shift. Tasks performed less than three total times were excluded from analyses, resulting in 15 tasks comprising 90% (117) of all (130) tasks performed during the study. Job tasks analyzed, as well as the number of times each task was performed, included: cable pull (3), electrical tools (3), jackleg drilling (3), grinding (4), blowing bench (5), air impact (6), welding (6), loading (7), jumbo drill operation (8), pumping water (9), tug operation (11), plasma cutting (11), support services (11), chipping (14), and mucking (16). No air impact, blowing bench, cable pulling, jackleg drilling, jumbo drilling, or mucking tasks were performed during the day shift, while no electrical tools tasks occurred on the swing shift, and no loading or water pumping tasks were performed during the night shift.

Both the day and swing shifts were worked with equal frequency (20), while the night shift was worked 16 times. Twenty-three and 33 shifts were worked in the #9 and #10 shafts, respectively.

MSHA PEL

Table I contains a summary of TWA_8 dosimetry for each type of dosimeter. The median noise TWA_8 for traditional dosimetry was not significantly different ($p = 0.6271$) from the MSHA PEL. The median TWA_8 for in-ear dosimetry was significantly lower ($p < 0.001$) than the MSHA PEL. Forty-five percent (17) of traditional TWA_8 measurements exceeded the MSHA PEL (90 dBA, respectively). A total of 16% (7) of in-ear TWA_8 measurements were $\geq$90 dBA. Seventy-six percent (29) of traditional dosimetry values and 33% (14) of in-ear TWA_8 measurements were greater than the MSHA Hearing Conservation threshold of 85 dBA.

TABLE I. Summary of Traditional and In-ear Dosimetry for MSHA TWA_8 Measures, as Well as the Observed Differences Between Dosimeter Types

	Traditional TWA_8 (dBA)	In-Ear TWA_8 (dBA)	Difference in TWA_8 (dBA)
n	38	43	25
Mean (±SD)	90.1 (±8.2)	80.3(±13.7)	10.5 (±8.4)
Median	89.8	**82**	9
95% CI	87.4–92.8	76.1–84.5	6.9–14.1

Bold: Significantly different from MSHA PEL TWA_8 at $p < 0.05$.

Job Task

A summary of noise exposure data by job task is listed in Table II. The traditional dosimetry TWA_8 noise exposures for those performing blowing bench ($p = 0.026$), jumbo drilling ($p = 0.002$), and mucking ($p < 0.001$) tasks were significantly greater compared to those who did not perform them. Those performing jumbo drill operation tasks also had significantly higher in-ear TWA_8 noise exposures ($p = 0.034$). For bench blowing, cable pulling, grinding, and jumbo drill operation tasks, the mean in-ear TWA_8 was greater than 85 dBA.

Shift and Location

Table III contains a summary of noise TWA_8 exposures by location and shift. From the Wilcoxon rank-sum test, miners working the day shift were exposed to lower noise levels, via traditional dosimeters, significantly so compared to those working swing ($p = 0.002$), but not night ($p = 0.096$) shifts. There was no difference in observed noise TWA_8 exposures between locations, neither for traditional nor in-ear dosimetry.

Hearing Protection Type

Table IV contains a summary of the effectiveness of the different HPD models compared to their adjusted NRRs. There was no statistically significant difference observed between the type of hearing protector and difference in TWA_8. Compared to their adjusted NRR, the median difference in TWA_8 for Acusonix (7.6 dBA) earplugs was significantly lower ($p = 0.0461$) than its adjusted NRR (11.5 dBA). The median difference in TWA_8 for Fusion S (9.4 dBA) earplugs was not significantly different ($p = 0.754$) from its adjusted NRR (9 dBA).

Correlation and Regression

The relationship between traditional and in-ear dosimetry TWA_8 revealed highly significant, positive correlation parameters for both Pearson's ($r = 0.581$, $p < 0.001$) and Spearman's rank ($r_s = 0.638$, $p < 0{,}001$) tests. For six out of the 33 shifts the reduction was negative, i.e., the average in-ear measurement was higher than the average dosimeter

TABLE II. Summary of Traditional and In-ear Dosimetry for MSHA TWA_8 Measures, as Well as the Observed Differences Between Dosimeter Types, by Job Task

Mean (±SD)	n[A]	Traditional TWA_8 (dBA)	In-Ear TWA_8 (dBA)	Difference in TWA_8 (dBA)
Air impact drilling	4,5,3	89.4 ± (15.2)	77.1 ± (14.5.0)	12.60 ± (1.1)
Blowing bench	2,5,2	**103.5 ± (0.9)**	87.8 ± (12.0)	9.85 ± (5.30)
Cable pulling	3,2,2	90.6 ± (6.7)	85.7 ± (4.6)	6.70 ± (3.8)
Chipping	12,10,8	90.3 ± (4.9)	83.9 ± (4.6)	6.6 ± (3.80)
Electrical tools	2,3,2	94.3 ± (13.9)	77.3 ± (11.9)	12.05 ± (2.2)
Grinding	4,3,3	90.2 ± (6.0)	86.6 ± (3.2)	4.6 ± (3.7)
Jackleg drilling	3,3,2	100.7 ± (7.7)	81.1 ± (21.4)	23.75 ± (20.7)
Jumbo drill operation	4,8,4	**103.0* ± (0.8)**	**88.3 ± (10.5)**	10.40 ± (7.9)
Loading	4,6,3	86.7 ± (4.1)	81.1 ± (7.1)	6.53 ± (3.8)
Locomotive operation	6,10,5	89.2 ± (3.5)	**70.1 ± (20.7)**	15.1 ± (10.5)
Mucking	8,15,7	**99.6[B] ± (4.7)**	84.5 ± (11.6)	13.36 ± (12.6)
Plasma cutting	9,8,7	91.1 ± (6.2)	82.5 ± (7.3)	8.3 ± (2.70)
Pumping water	7,8,6	93.9 ± (8.3)	77.6 ± (15.4)	**20.8 ± (12.4)** [B]
Support services	8,9,6	85.2 ± (7.0)	76.2 ± (9.1)	7.80 ± (4.1)
Welding	6,5,5	88.2 ± (7.0)	80.4 ± (13.8)	10.8 ± (13.20)

Note: Bold: Significantly different from those not performing task at $p < 0.05$.
[A]Where some data are missing, sample size (n) is listed in the following order: traditional dosimetry, in-ear dosimetry, difference in TWA_8.
[B]Significantly different from those not performing the task at $p < 0.01$.

TABLE III. Summary of Traditional and In-ear Dosimetry for MSHA TWA_8 Measures, as Well as the Observed Differences Between Dosimeter Types, by Shift and Location

Mean (±SD)	n^A	Traditional TWA_8 (dBA)	In-Ear TWA_8 (dBA)	Difference in TWA_8 (dBA)
Day Shift	15,14,9	**85.6**^{B} ± **(5.6)**	73.4 ± (18.8)	10.3 ± (9.9)
Swing Shift	13,18,11	**95.4**^{B} ± **(7.3)**	83.8 ± (11.8)	12.24 ± (10.3)
Night Shift	10,14,8	89.8 ± (9.2)	82.7 ± (6.5)	8.2 ± (3.8)
Shaft #9	19,16,10	88.7 ± (6.4)	82.1 ± (6.6)	7.4 ± (3.0)
Shaft #10	19,30,15	91.5 ± (9.7)	79.5 ± (16.1)	12.6 ± (10.5)

Note: **Bold:** Significantly different from those not working shift at $p < 0.05$.
^{A}Where some data are missing, sample size (n) is listed in the following order: traditional dosimetry, in-ear dosimetry, difference in TWA_8.
^{B}Significantly different from those not working shift at $p < 0.01$.

measurement. Primary analysis was performed with the six negative noise reduction values unchanged, and sensitivity analysis was conducted with the six negative values imputed as 0. The average noise reduction level ranged from -5.5 to 38.4 dBA, with mean 8.2 ± 9.0 dBA and median 7.4 dBA. The non-negative (possibly imputed) average noise reduction level ranged from 0 to 38.4, with mean 8.6 ± 8.6 dBA and median 7.4 dBA. Positive correlation parameters were observed for Pearson's ($\rho = 0.240$) and Spearman's rank ($r_s = 0.240$) tests, but there was no evidence they were different from zero ($p = 0.179$ and $p = 0.178$, respectively).

DISCUSSION

MSHA PEL

In this study, personal hearing protection was clearly necessary, as observed traditional dosimetry measures were all very close to, or above, the MSHA PEL—indicating an inadequacy of existing engineering and administrative controls. Despite these and personal controls—as well as the retraining and fit-testing each miner received during this study—almost one-third of miners were still exposed to greater than 85 dBA via in-ear dosimetry during their shift. Given the prevalent and pervasive nature of noise in mining this is unsurprising, but disturbing nonetheless.

Job Tasks

Noise exposures from blowing bench, chipping, jackleg drilling, jumbo drill operation, mucking, and related tasks can be particularly high and difficult to control.[21–25] Our findings are consistent with these data. Most concerning are those job tasks (blowing bench, cable pulling, grinding, and jumbo drill operation) whose mean in-ear TWA_8 measurements were greater than 85 dBA, indicating that all controls likely failed to prevent those miners from experiencing hearing damage. Engineering and administrative controls were least effective for those performing blowing bench, mucking, and jackleg and jumbo drilling tasks—as each had a measured, mean traditional dosimeter TWA_8 greater than 99 dBA.

Shift and Location

The engineering and administrative controls utilized during the day shift and in the #9 Shaft appear to provide better protection than during swing and night shifts, or in Shaft #10. Interestingly, personal hearing protection was much more effective for miners in Shaft #10, as their in-ear TWA_8 measurements were lower than those in Shaft #9—despite Shaft #9's lower traditional dosimetry measures. The reason for these differences is unclear, but is likely due, in part, to both the specific nature of activities conducted during the time of the study within each shaft and the distribution of job tasks among shifts, with the loudest tasks occurring during swing and night shifts. Unexpectedly, the authors were not able to locate other

TABLE IV. Summary of Adjusted NRR, as Well as Mean and Median Observed Differences in TWA_8 (dBA)

	n	Manufacturer NRR	Adjusted NRR	Mean Observed Difference in TWA_8	Median Observed Difference in TWA_8
Acusonix	11	30	11.5	12.7	**7.6**
Fusion LG	1	25	9	9.0	9.0
Fusion S	10	25	9	9.2	9.3
Matrix	2	29	11	7.5	7.5
Smartfit	1	25	9	7.1	7.1

Note: **Bold:** Significantly different from the adjusted NRR at $p < 0.05$.

studies comparing the noise exposures of underground miners during different work-shift rotations.

Hearing Protection Type

This study evaluated the raw attenuation of HPDs of five different types during full-shift operations in an underground mining setting. However, our ability to critically evaluate the different types of HPD was severely limited by sample size, and compounded by improper use of the HPDs. It appears that, in our study, the 50% correction factor recommended by OSHA for estimating the actual noise reduction provided by HPDs was necessary, as raw mean and median differences in TWA_8 tended to be very similar to or below the adjusted NRR. Only one earplug type (Fusion S) had observed mean and median above the adjusted NRR—though it was not statistically different. For evaluating the attenuation efficacy of HPDs, laboratory and workplace environments differ dramatically, as evidenced by studies investigating the labeled attenuation and environmental measurements.[26–29] Several factors affect earplugs' actual reduction of noise exposures, including proper use by and the fit in the individual worker, as well as the practice and type of earplug insertion training.[30,31] Although we observed a high rate of improper HPD use, despite earplug fit-testing and insertion training, we believe the rate would have been higher without it. In addition, our study was not designed to evaluate the effectiveness of earplug insertion training or fit-testing, and believe further work in this area is warranted.

Correlation and Regression

The highly significant correlation between traditional and in-ear dosimetry confirms that HPD efficacy was similar across the study. However, the measured attenuation demonstrates that the use of HPDs as a primary noise control is inadequate, even when retraining and fit-testing occur.

LIMITATIONS

Our study is limited by its small sub-group sample sizes, as well as recall and other biases introduced via the job task questionnaire. Research team members were not permitted to observe the miners underground while they performed their tasks. Neither actual HPD use nor task times were estimated. Also, it is disturbing that such a high proportion (36%) of our data had to be removed because the in-ear TWA_8 measurements were higher than the corresponding shoulder TWA_8—despite the earplug insertion training and fit-testing provided at the beginning of the study. Although the cause of such results is unclear, the authors believe these results may be attributed to improper use of HPD, as all devices were calibrated and some anecdotal evidence from in-ear inserts indicated that plugs were likely misused or unused (covered in mud, broken wires, and so on). The causative factors and frequency of such occupational behavior is unclear and warrants further investigation.

No adjustments were made to analyses to account for confounding factors across groups, such as shift worked or job tasks performed. Anecdotally, what appeared to be significant inconsistency with HPD donning within the same individual, during the same shift and across shifts was observed. This is indicative of broad inconsistent hearing protective factors and the importance of behaviors related to use of HPDs, warranting further study.

CONCLUSION

When this cumulative intervention evaluation approach is applied in active underground mining environments, quantifiable measures of noise-control effectiveness can be used to increase the likelihood that noise control decisions have the two desired results, i.e., preserving the present hearing thresholds of workers and reducing occupational noise exposure to below regulatory levels.

In this study, 44% of noise TWA_8 exposures exceeded the MSHA PEL, despite existing engineering and administrative controls, while the use of HPDs protected most workers from excessive noise levels. Mine operators should focus on improving engineering and administrative controls for the noisiest tasks and shifts, and ensure that miners are frequently hearing protector fit-tested and receive regular earplug insertion training and audiograms. There was some variation in noise exposure by job task and shift, and exposure measurements were significantly correlated between dosimeter types.

This research establishes a foundation upon which mine operators performing deep shaft sinking activities can base their noise exposure evaluation and intervention strategies, targeting those job tasks and shifts most likely to be at risk of over-exposure and hearing damage and underscores the prevalent nature of high occupational noise exposures in this mine, the importance of noise intervention confirmation, and the correlation of traditional with in-ear dosimetry.

ACKNOWLEDGMENTS

We would like to sincerely thank the miners who volunteered to participate in this study. Further, this work would not be possible without the extensive support of Shannon Newton and assistance of Jonathan Piakis and Cassandra Porchas.

FUNDING

This work was funded through the Science Foundation Arizona Grant #SRG 0330-08.

REFERENCES

1. **McBride, D.I.:** Noise-induced hearing loss and hearing conservation in mining. *Occup. Med.-Oxford 54*(5):290–296 (2004).

2. **Nelson, D.I., R.Y. Nelson, M. Concha-Barrientos, et al.:** The global burden of occupational noise-induced hearing loss. *Am. J. Indus. Med. 48*(*6*):446–458 (2005).
3. **Edwards, A.L., J.J. Dekker, R.M. Franz, et al.:** Profiles of noise exposure levels in South African mining. *J. South African Inst. Mining Metallur. 111*(*5*):315–322 (2011).
4. **Attarchi, M., F. Dehghan, F. Safakhah, et al.:** Effect of exposure to occupational noise and shift working on blood pressure in rubber manufacturing company workers. *Indus. Health 50*(*3*):205–213 (2012).
5. **Chang, T.Y., R.M. Jain, C.S. Wain, et al.:** Effects of occupational noise exposure on blood pressure. *J. Occup. Environ. Med. 45*(*12*):1289–1296 (2003).
6. **Chang, T.Y., T.C. Su, S.Y. Lin, et al.:** Effects of occupational noise exposure on 24-hour ambulatory vascular properties in male workers. *Environ. Health Perspect. 115*(*11*):1660–1664 (2007).
7. **Davies, H.W., K. Teschke, S.M. Kennedy, et al.:** Occupational exposure to noise and mortality from acute myocardial infarction. *Epidemiology 16*(*1*):25–32 (2005).
8. **Davies, H., and I. Van Kamp:** Noise and cardiovascular disease: A review of the literature 2008–2011. *Noise & Health 14*(*61*):287–291 (2012).
9. **Melamed, S., Y. Fried, and P. Froom:** The joint effect of noise exposure and job complexity on distress and injury risk among men and women: The Cardiovascular Occupational Israel Study. *J. Occup. Environ. Med. 46*(*10*):1023–1032 (2004).
10. **Lusk, S.L., B.M. Hagerty, B. Gillespie, et al.:** Acute effects of noise on blood pressure and heart rate. *Arch. Environ. Health 59*(*8*): 392–399 (2004).
11. **Dias, A., and R. Cordeiro:** Attributable fraction of work accidents related to occupational noise exposure in a southeastern city of Brazil. *Cadernos De Saude Publica 23*(*7*):1649–1655 (2007).
12. **Cordeiro, R., A.P.G. Clemente, C.S. Diniz, et al.:** Occupational noise as a risk factor for work-related injuries. *Revista De Saude Publica 39*(*3*):461–466 (2005).
13. **Girard, S.A., M. Picard, A.C. Davis, et al.:** Multiple work-related accidents: Tracing the role of hearing status and noise exposure. *Occup. Environ. Med. 66*(*5*):319–324 (2009).
14. **Picard, M., S.A. Girard, M. Simard, et al.:** Association of work-related accidents with noise exposure in the workplace and noise-induced hearing loss based on the experience of some 240,000 person-years of observation. *Accid. Anal. Prev. 40*(*5*):1644–1652 (2008).
15. **Tak, S., R.R. Davis, and G.M. Calvert:** Exposure to hazardous workplace noise and use of hearing protection devices among US workers - NHANES, 1999–2004. *Am. J. Indus. Med. 52*(*5*):358–371 (2009).
16. **Tak, S., and G.M. Calvert:** Hearing difficulty attributable to employment by industry and occupation: An analysis of the National Health Interview Survey - United States, 1997 to 2003. *J. Occup. Environ. Hyg. 50*(*1*):46–56 (2008).
17. **Masterson, E.A., S. Tak, C.L. Themann, et al.:** Prevalence of hearing loss in the United States by industry. *Am. J. Indus. Med. 56*(*6*):670–681 (2013).
18. **National Institute for Occupational Safety and Health (NIOSH):** Criteria for a Recommended Standard: Occupational Noise Exposure, 1998.
19. **Landen, D., S. Wilkins, M. Stephenson, et al.:** Noise exposure and hearing loss among sand and gravel miners. *J. Occup. Environ. Med 1*(*8*):532–541 (2004).
20. **Hansia, M.R., and D. Dickinson:** Hearing protection device usage at a South African gold mine. *Occup. Med.-Oxford 60*(*1*):72–74(2010).
21. **Phillips, J.I., P.S. Heyns, and G. Nelson:** Rock drills used in South African mines: A comparative study of noise and vibration levels. *Ann. Occup. Hyg. 51*(*3*):305–310 (2007).
22. **Roy, S., and G.R. Adhikari:** Worker noise exposures from diesel and electric surface coal mining machinery. *Noise Control Eng. J. 55*(*5*):434–437 (2007).
23. **Seal, A.B., and C.J. Bise:** Case study using task-based, noise-exposure assessment methods to evaluate miner noise hazards. *Mining Eng. 54*(*11*):44–48 (2002).
24. **Sensogut, C.:** Occupational noise in mines and its control - A case study. *Polish J. Environ. Stud. 16*(*6*):939–942 (2007).
25. **Szary, M.L., Y.P. Chugh, and J. Hirschi:** Noise variability in underground room and pillar coal mines. *Int. J. Occup. Safety Ergon. 17*(*3*):301–308 (2011).
26. **Berger, E.H., J.R. Franks, and F. Lindgren:** International review of field studies of hearing protector attenuation. *Sci. Basis of Noise-Induced Hear. Loss*:361–377 (1996).
27. **Giardino, D.A., and G. Durkt:** Evaluation of muff-type hearing protectors as used in a working environment. *Am. J. Indus. Med. 57*(*3*):264–271 (1996).
28. **Neitzel, R., and N. Seixas:** The effectiveness of hearing protection among construction workers. *J. Occupa. Environ. Hyg. 2*(*4*):227–238 (2005).
29. **Nelisse, H., M.A. Gaudreau, J. Boutin, et al.:** Measurement of hearing protection devices performance in the workplace during full-shift working operations. *Ann. Occup. Hyg. 56*(*2*):221–232 (2012).
30. **Joseph, A., J. Punch, M. Stephenson, et al.:** The effects of training format on earplug performance. *Int. J. Audiol. 46*(*10*):609–618 (2007).
31. **Toivonen, M., R. Paakkonen, S. Savolainen, et al.:** Noise attenuation and proper insertion of earplugs into ear canals. *Ann. Occup. Hyg. 46*(*6*):527–530 (2002).